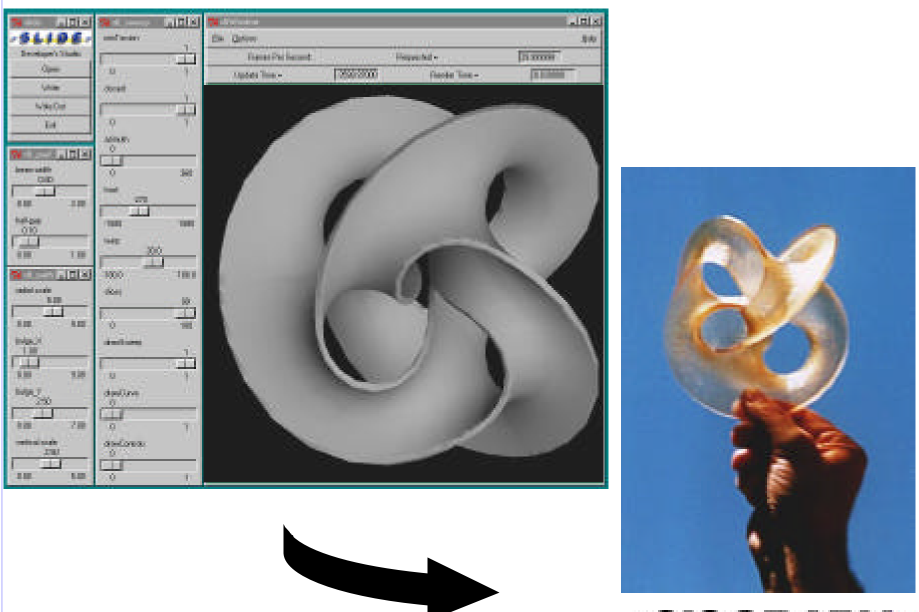
3D Hardcopy: Converting Virtual Reality to Physical Models

Sara McMains
Carlo Séquin } U.C. Berkeley
Mike Bailey SDSC & UCSD
Rich Crawford U.T. Austin

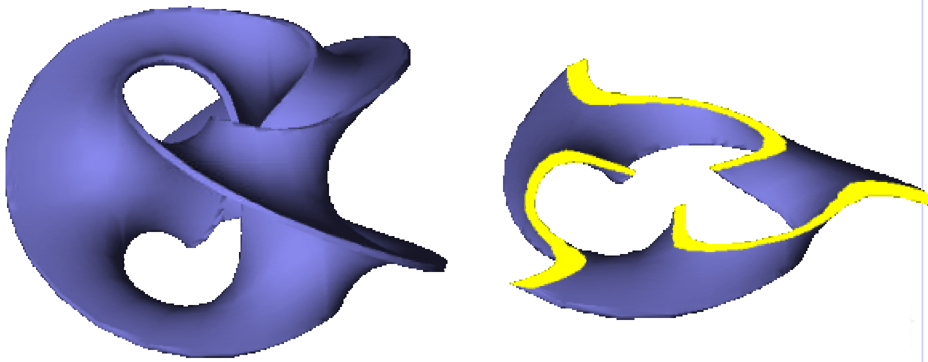


Layered Manufacturing (LM)

a.k.a. Solid Freeform Fabrication (SFF)

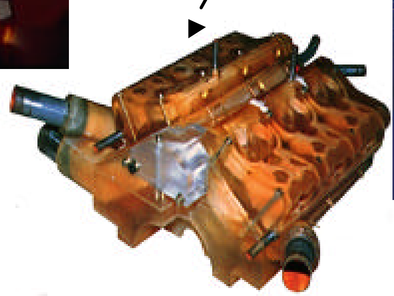
a.k.a. Rapid Prototyping (RP)

Automated build of complex 3D shapes from 2.5-D layers



Industrial Applications of LM

- Design review
- Positives for molds
- Functional testing



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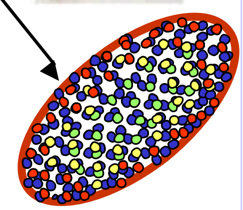
Medical Applications of LM

- Prosthetics
- Pharmaceuticals
  - Micro-structure control
- Tissue engineering



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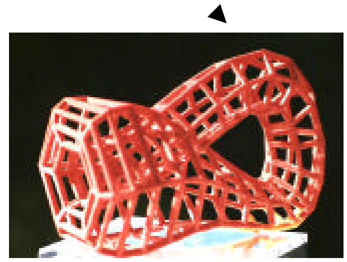
Educational Applications of LM

San Diego Harbor
(Bailey)

- Scientific Visualization
- Topological Models
- Tactile Mathematics

Hyperbolic paraboloid w/ Braille annotations (Stewart Dickson)

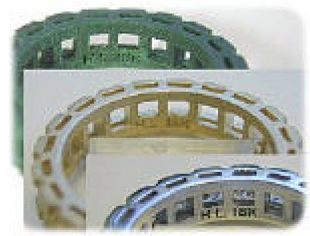


Klein Bottle Skeleton (Séquin)

Artistic Applications of LM

- Jewelry
- Sculpture

“Ora Squared”
(Bathsheba Grossman)



Commercial LM Technologies - U.S.

Subtractive
- Laminated Object Manufacturing (LOM)

Additive with sacrificial supports
- Thermoplastic deposition
  - Multi-Jet Modeling (MJM)
  - Solidscape’s ModelMaker
  - Fused Deposition Modeling (FDM)
- Stereolithography (SLA)

Powder solidification
- 3D Printing (3DP)
- Selective Laser Sintering (SLS)

Speakers : Mike Bailey

PhD: Purdue

- Mechanical Engineering

Senior Principal Scientist, San Diego Supercomputer Center

- Tele-manufacturing Project

Adjunct Professor, UCSD Computer Science and Mechanical Engineering

Speakers : Carlo Séquin

PhD: University of Basel, Switzerland

- Experimental Physics (Solid State Devices)

Professor, U.C. Berkeley - Computer Science

- Computer-Aided Design
- Computer Graphics
- Geometric Modeling

Speakers : Rich Crawford

PhD: Purdue

- Mechanical Engineering

Professor, U.T. Austin - Mechanical Engineering

- Design Methodology
- Geometric Modeling for Design

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Speakers : Sara McMains

PhD: U.C. Berkeley

- Computer Science

Postdoctoral Researcher, U.C. Berkeley Computer Science

- Layered Manufacturing
- Virtual Reality

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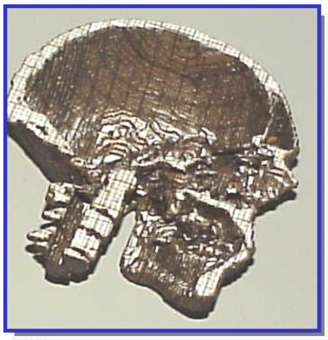
Laminated Object Manufacturing



Mike Bailey
San Diego Supercomputer Center
University of California San Diego
`mjb@sdsc.edu`

CENTER FOR VISUALIZATION PROTOTYPES
AT THE SAN DIEGO SUPERCOMPUTER CENTER

Currently sold and maintained by:

Cubic Technologies
1000 East Dominguez Street
Carson, CA 90746-3608
310-965-0006
F: 310-965-0141
`http://www.cubictechnologies.com`

LOM Process

• Builds solids from layers of paper or plastic

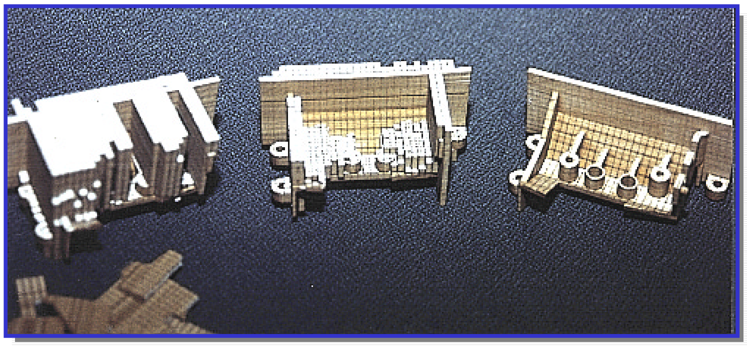
• Uses heat and pressure to laminate a new layer to the layers beneath it

• Uses a CO_2 laser to cut the outline of the 3D part at that layer

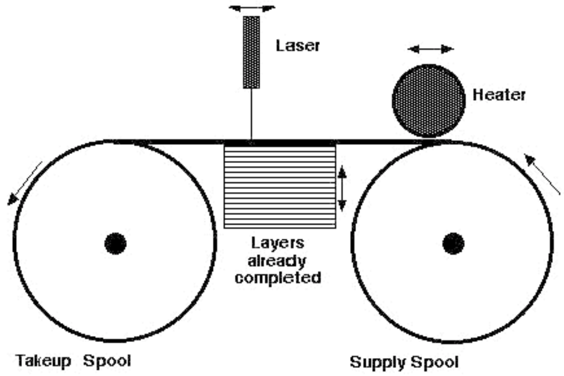
• Leaves scrap in place to support overhangs

• Cross-hatches the scrap to make it easier to remove later

The De-scrapping Process



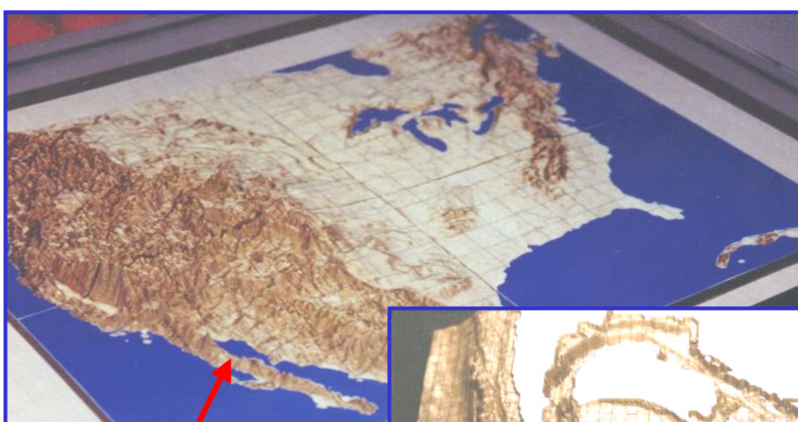
Helisys LOM 1015



Helisys LOM 1015

LOM Characteristics

- Paper thickness is ~ .0044”
- Parts made from paper look and feel like wood
- Paper parts absorb moisture from the air if not coated
- Parts are very strong in compression, weak in tension
- You can sand, drill, nail, screw, bolt, paint, stain, varnish LOM parts
- You get “free” contour lines and “slope shading” (terrain people really like this)
- Parts made from plastic are waterproof

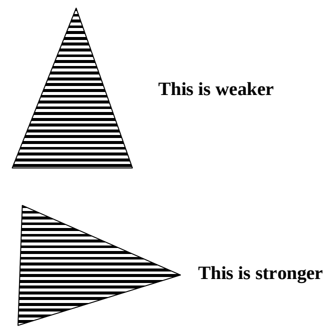


Free contour lines

LOM Characteristics

Like all RP technologies, LOM has an optimal orientation that is a compromise between:

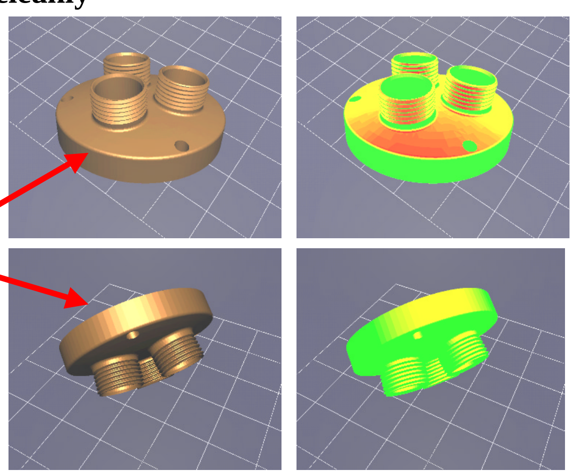
- **Build time**
- **Appearance**
- **Strength**
- **Ease of de-scrapping**



Ease of De-scrapping

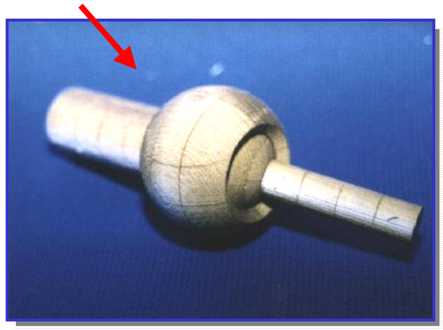
The more horizontal a surface is, the harder it is to de-scrap cleanly

Changing the orientation will move the difficult de-scrapping area to somewhere less crucial



9 Fitted Plates

Burn out the gap to make a working joint



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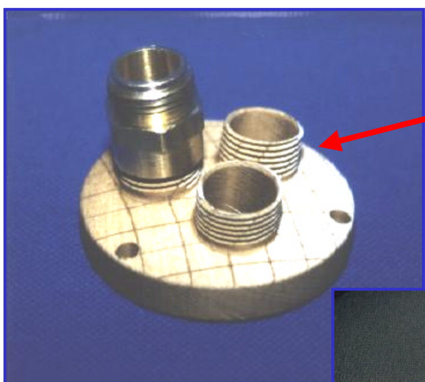
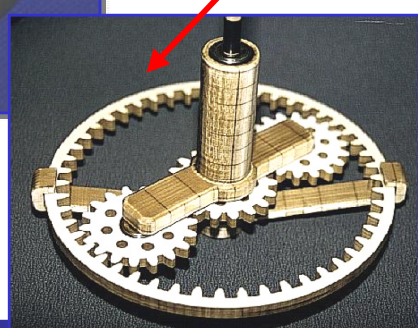
San Diego Supercomputer Center SDSC



Screw threads

Gear teeth



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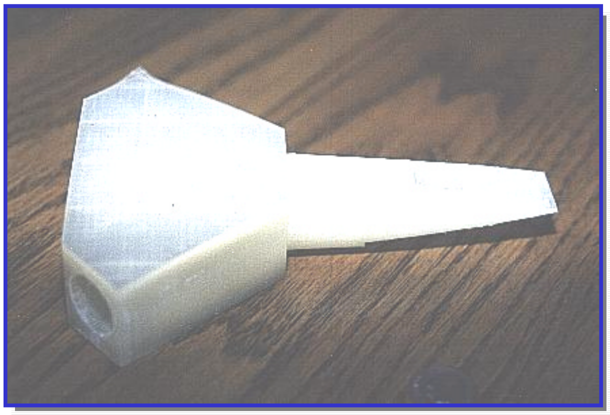
LOM Plastic Part



Yes, but, what is it??

UCSD University of California San Diego San Diego Supercomputer Center SDSC

Thank You !

Mike Bailey
`mjb@sdsc.edu`

http://www.sdsc.edu/~mjb
http://cvp.sdsc.edu

UCSD University of California San Diego San Diego Supercomputer Center SDSC

SFF

Commercial SFF Processes (cont.)

Additive Methods with Sacrificial Supports

- Solid Printing / Imaging (3D Systems)
- Solidscape (Sanders Prototype, Inc.)
- Fused Deposition Modeling (Stratasys)
- Stereolithography

Powder Bed Based Approaches

- 3D Printing (Z-Corporation)
- Selective Laser Sintering

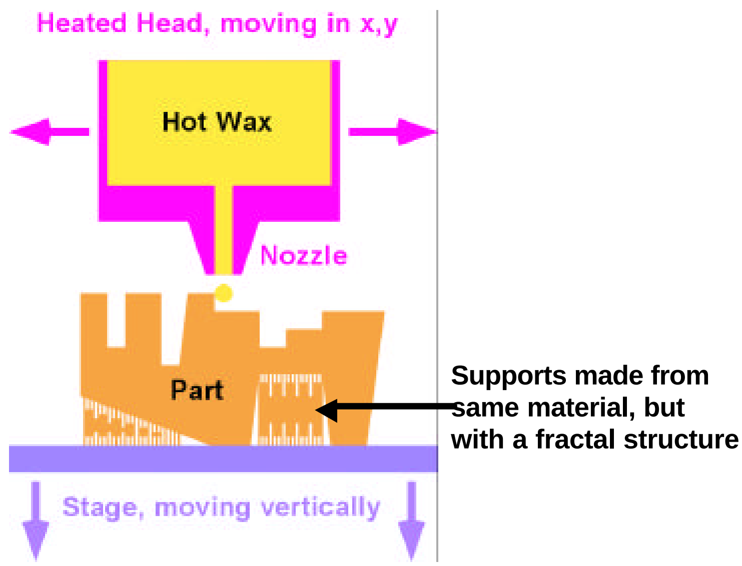
SFF

SFF: Solid Object-Printing / Imaging

- Droplets of a thermoplastic material are sprayed from a moving print head onto a platform surface.
- Need to build a support structures where there are overhangs / bridges.
- These supports (of the same material) are given porous, fractal nature.
- They need to be removed (manually).
- Key player: 3D Systems: http://www.3dsystems.com/index_nav.asp

SFF

SFF: Solid Object Printing



SFF

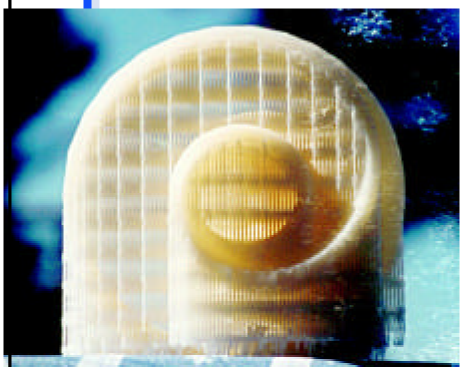
SFF: Solid Object Printing

Thermojet Printer (3D Systems)

- **Technology: Multi-Jet Modeling (MJM)**
- **Resolution (x,y,z): 300 x 400 x 600 DPI**
- **Maximum Model Size: 10 x 7.5 x 8 in (13 lb)**
- **Material: neutral, gray, black thermoplastic:**
  - **ThermoJet 88: smooth surfaces for casting**
  - **ThermoJet 2000: more durable for handling**

SFF

SFF: Solid Object Printing



- That's how parts emerge from the Thermojet printer
- After partial removal of the supporting scaffolding

SFF

SFF: Solid Object Printing

An Informal Evaluation

- Fast
- Inexpensive
- Reliable, robust
- Support removal takes some care (refrigerate model beforehand)
- Thermojet 88 parts are fragile
- Good for investment casting

SFF

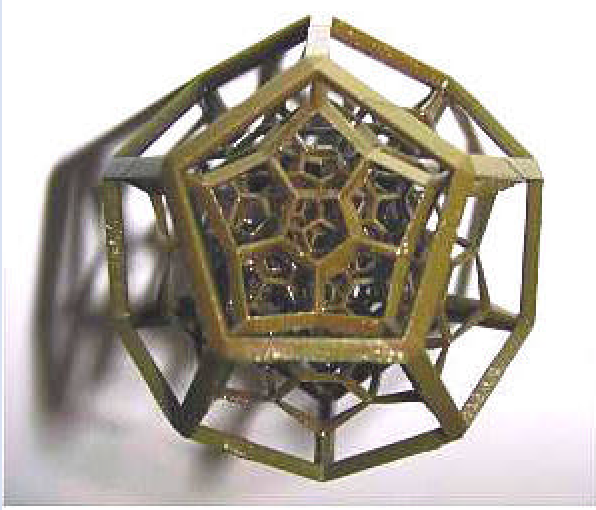
SFF: Solid Object Printing

ModelMaker II (Solidscape)

- Alternate Deposition / Planarization Steps
  - Build envelope: 12 x 6 x 8.5 in.
  - Build layer: 0.0005 in. to 0.0030 in.
  - Achievable accuracy: +/- 0.001 in. per inch
  - Surface finish: 32-63 micro-inches (RMS)
  - Minimum feature size: 0.010 in.
- Key Player:
  Solidscape: http://www.solid-scape.com/

SFF

SFF: Solid Object Printing



(2" diam.)

Projection of 4D 120-cell, made in "jewelers wax."

SFF

SFF: Solid Scape (Sanders)

An Informal Evaluation

- The precisest SFF machine around
- Very slow
- Sensitive to ambient temperature
- Must be kept running most of the time
- Poor software
- Little access to operational parameters

Based on comments by B. G.: http://www.bathsheba.com/

SFF

SFF: Fused Deposition Modeling

Principle:

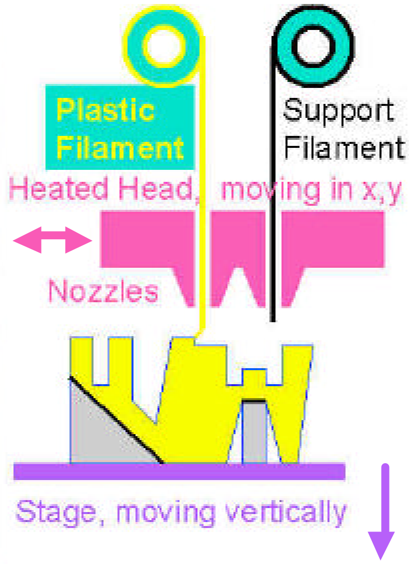
- Beads of semi-liquid ABS plastic get deposited by a head moving in x-y-plane
- Supports are built from a separate nozzle

- Key player:
  Stratasys: http://www.stratasys.com/

Schematic view ==>

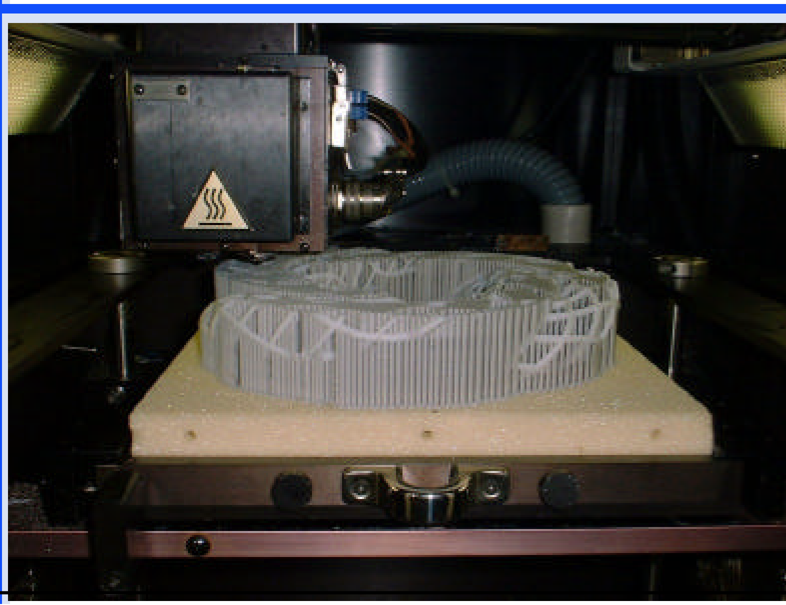
SFF

Fused Deposition Modeling



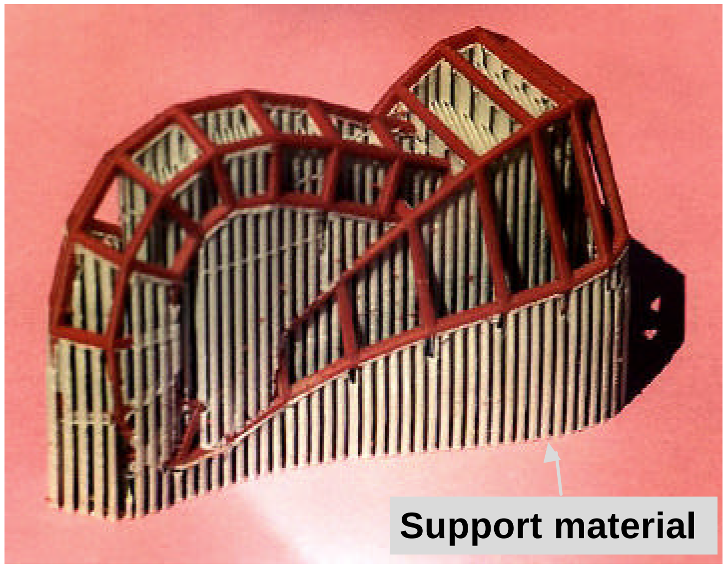
SFF

Looking into the FDM Machine



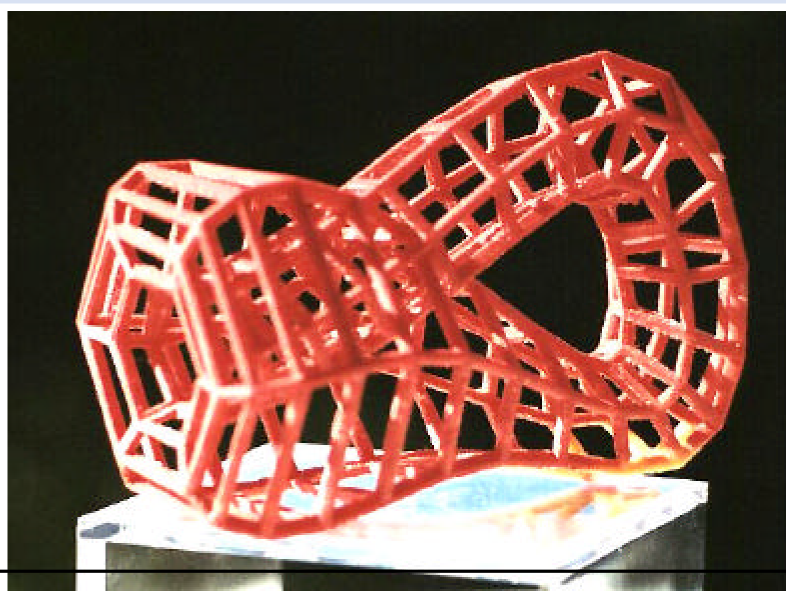
SFF

Layered Fabrication of Klein Bottle



SFF

Klein Bottle Skeleton (FDM)



SFF

FDM: The Software Interface

Stratasys Quickslice

- Good “tutorial” for layered manufacturing
- Offers all the knobs a professional needs
- Several entry points:
  - STL: B-rep in triangle soup
  - SSL: Per-layer outline contours
  - SML: Actual x-y-path of head to fill each layer
- Too much automated clean-up “smarts” for overlaping contours
- Not enough convenient editing of contours

SFF

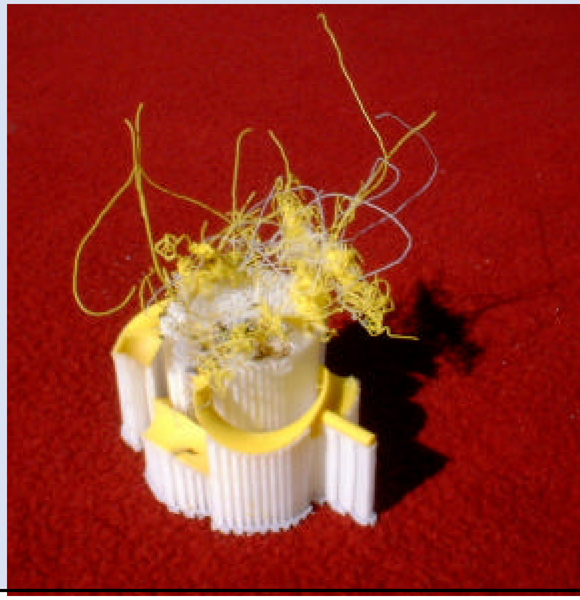
Fused Deposition Modeling

An Informal Evaluation

- Easy to use
- Rugged and robust
- Could have this in your office
- Good transparent software (Quickslice) with multiple entry points: STL, SSL, SML
- Inexpensive to operate
- Slow
- Think of support removal !

SFF

What Can Go Wrong ?



Black blobs

Toppled supports

SFF

Powder-based Approaches

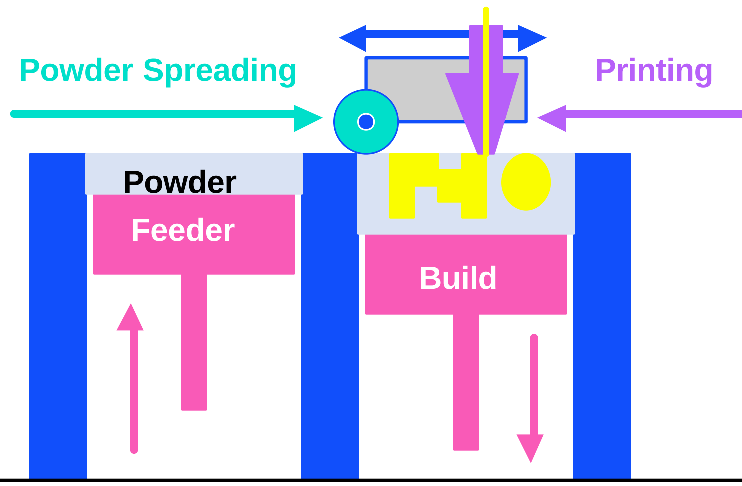
Key Properties:

- Needs no supports that must be removed!
- Uniform bed of powder acts as support.
- This powder gets selectively (locally) glued (or fused) together to create the solid portions of the desired part.

SFF

SFF: 3D Printing -- Principle

- Selectively deposit binder droplets onto a bed of powder to form locally solid parts.



SFF

3D Printing: Some Key Players

- Z Corporation: http://www.zcorp.com/
  Plaster and starch powders for visualization models.
- Soligen: http://www.soligen.com/
  Metal and ceramic powders for operational prototypes.
- Therics Inc.: http://www.therics.com/
  Biopharmaceutical products, tissue engineering.

SFF

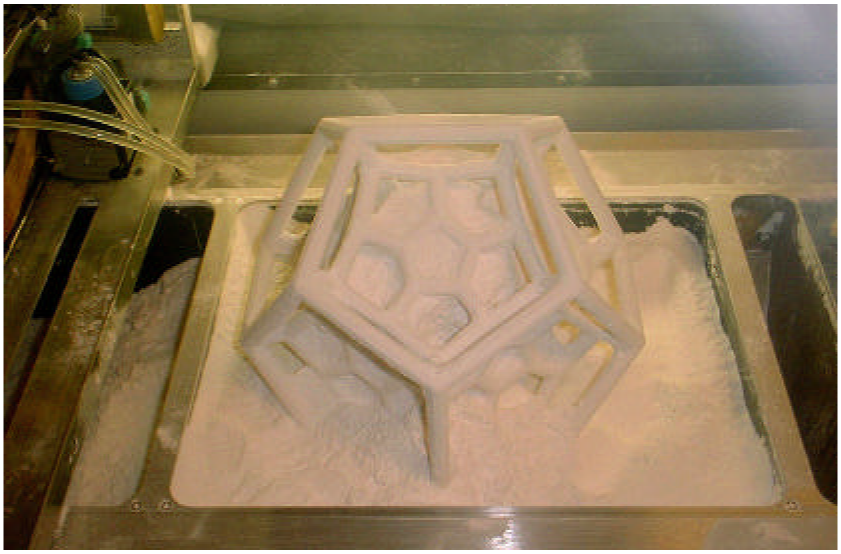
3D Printing: Z Corporation

The Z402 3D Printer

- Speed: 1-2 vertical inches per hour
- Build Volume: 8" x 10" x 8"
- Thickness: 3 to 10 mils, selectable

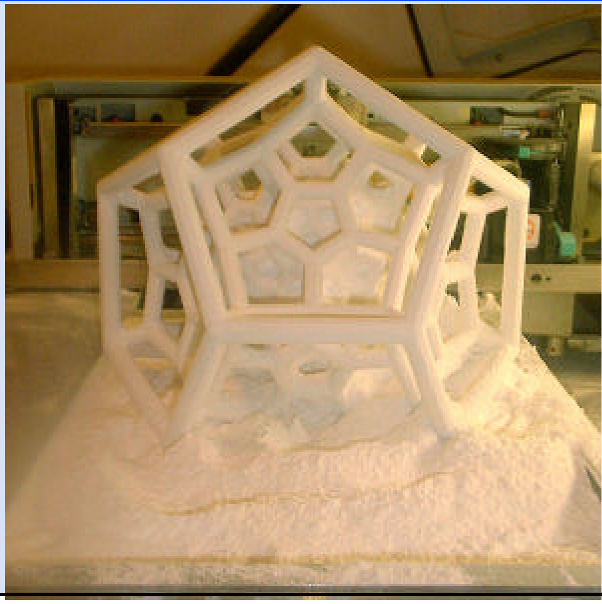
SFF

3D Printing: Z Corporation



SFF

3D Printing: Z Corporation



- Digging out

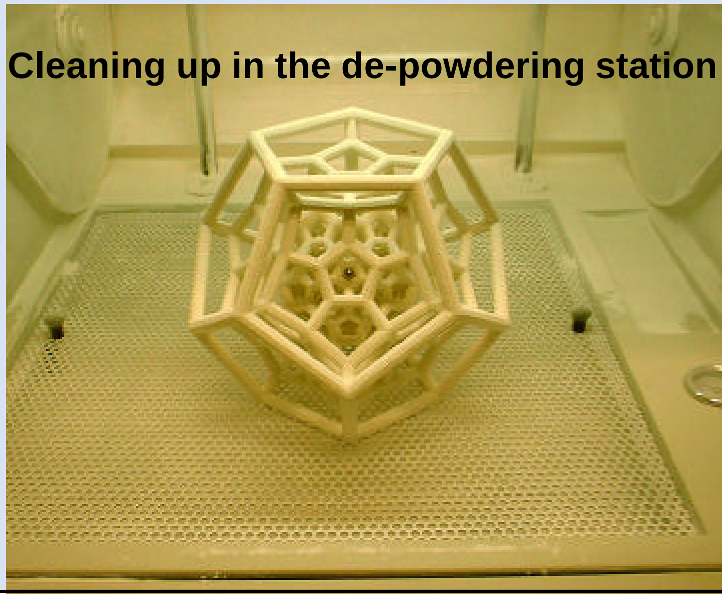
SFF

Optional Curing: 30 min. @ 200ºF

SFF

3D Printing: Z Corporation

Cleaning up in the de-powdering station



SFF

3D Printing: Z Corporation

The finished part

SFF

3D Color Printing: Z Corporation

The Z402C 3D Color Printer

Differences compared to mono-color printer:

- **Color print head with: Cyan, Yellow, Magenta, Black, and Neutral.**
- **Smaller build area.**

Specs:

- **Speed: 0.33 - 0.66 vertical inches per hour**
- **Build Volume: 6" x 6" x 6"**
- **Thickness: 3 to 10 mils, selectable**
- **Color depth: 80 mils**

SFF

3D Color Printing: Z Corporation

SFF

3D Color Printing: Z Corporation

Use compressed air to blow out central hollow space.

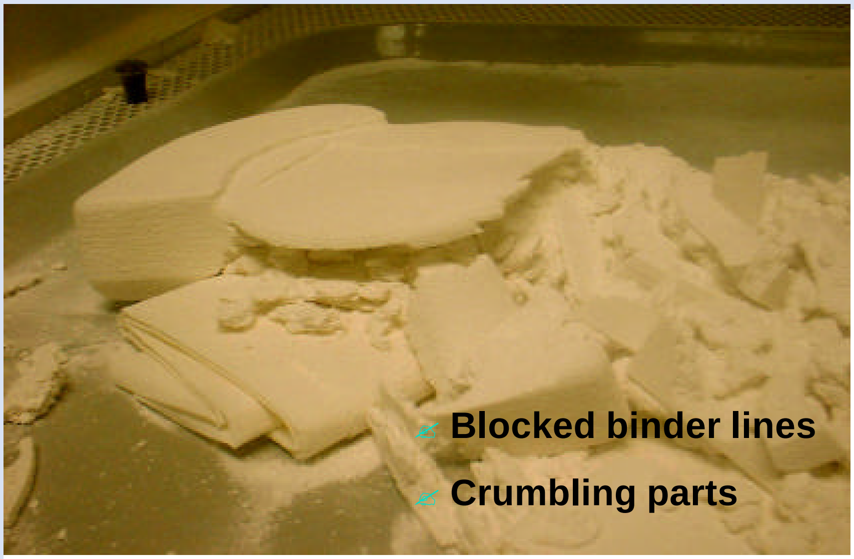
SFF

3D Color Printing: Z Corporation

Infiltrate Alkyl Cyanoacrylane Ester = “super-glue” to harden parts and to intensify colors.

SFF

What Can Go Wrong ?



SFF

Broken Parts

SFF

3D Printing: Z Corporation

An Informal Evaluation

- Fast !
- Running expenses: moderate, (but overpriced powder)
- Color print head and tubes need some care in maintenance.
- Somewhat messy cleanup !
- Lots of dust everywhere ...

Stereolithography (SLA)

Technology: *Curable Liquid Resin*

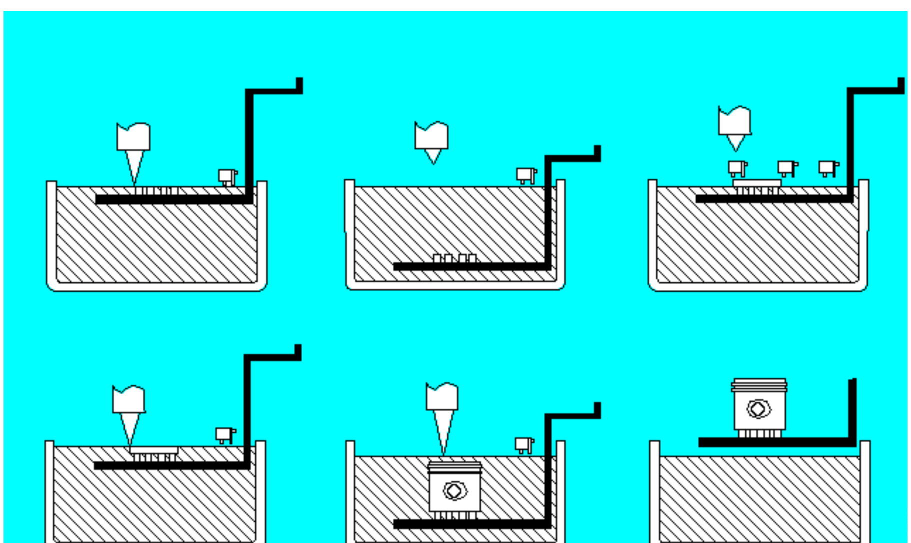
Introduced: *1988*

Major Vendors:

3D Systems

(www.3dsystems.com)

Sterolithography



Stereolithography

Process

- Parts scanned in "honeycomb" pattern that traps liquid resin
- Post-processed in UV oven

Applications

- Concept models
- Investment casting patterns
- Prototype tooling (Keltool)

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Selective Laser Sintering (SLS)

Technology: ***Laser fused powders***

Introduced: ***1992***

Major Vendor: ***DTM***

(www.dtm-corp.com)

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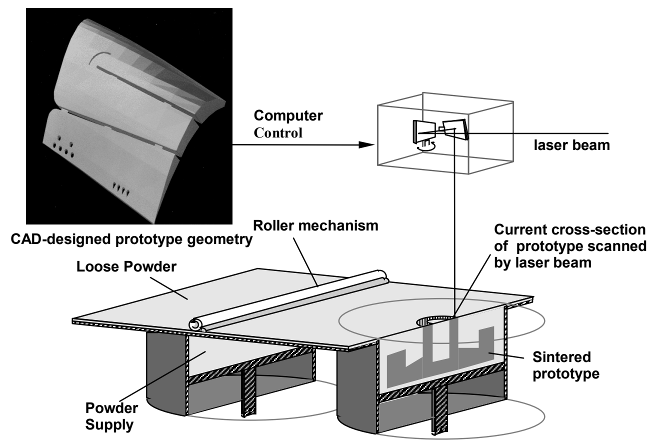
Selective Laser Sintering



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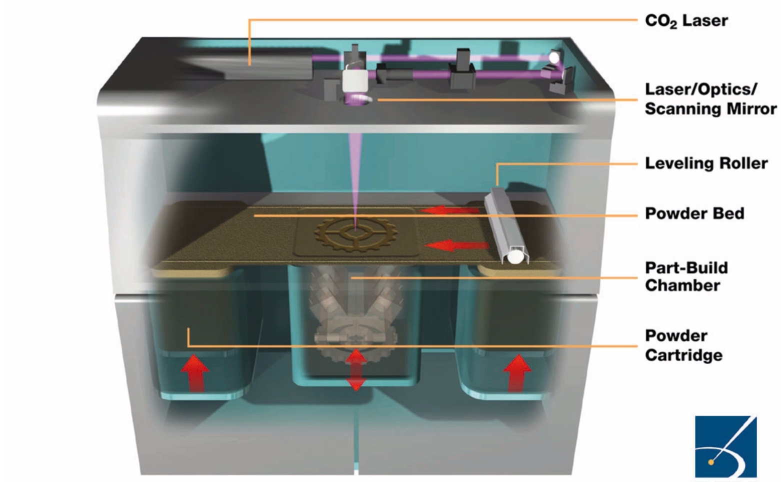
Selective Laser Sintering



DTM CORPORATION

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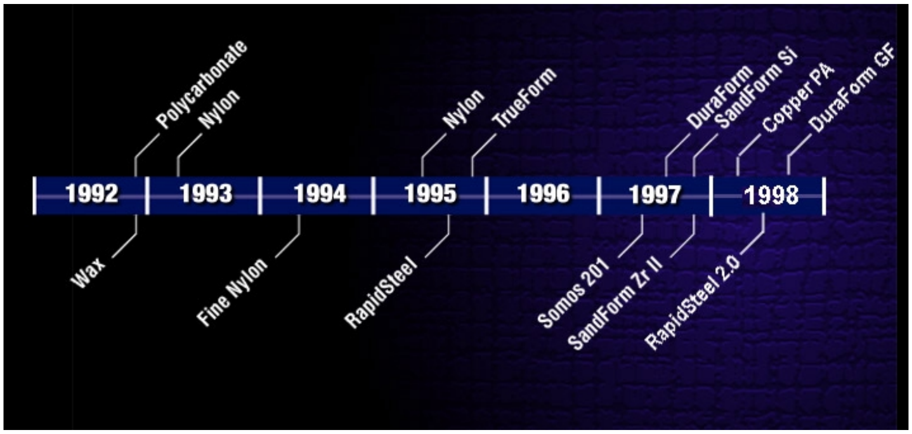
SLS Material Introduction Timeline



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Applications

Concept Models

- If a picture is worth a thousand words then is an object worth a thousand pictures?

Patterns

- Casting

Functional Prototypes

- Parts for design

Custom manufacturing

- Parts on demand

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Multiple Material SLS

Functional Gradient Material Fabrication

- Modifications to Selective Laser Sintering
- Discrete or continuous material distributions

If you could control the material properties at any point in a part, what could you make?

- How would you design it?
- How would you represent the material distribution?

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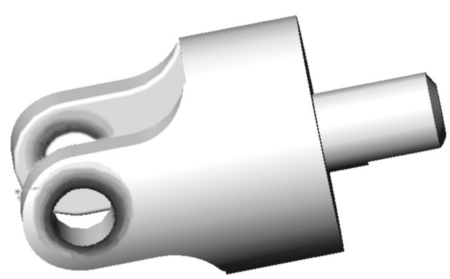
FGM Reinforced Component



- **Wear resistive material around pin holes**
- **Improved bonding**
- **Longer life in severe loading and temperature environment**

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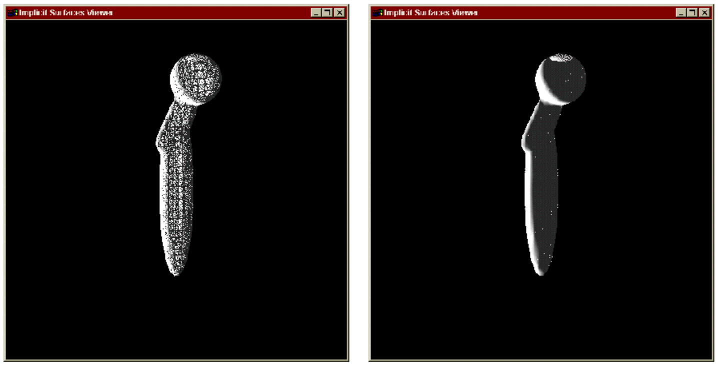
Hip Socket Implant



- Bioceramic exterior graded to ductile metal (titanium) interior

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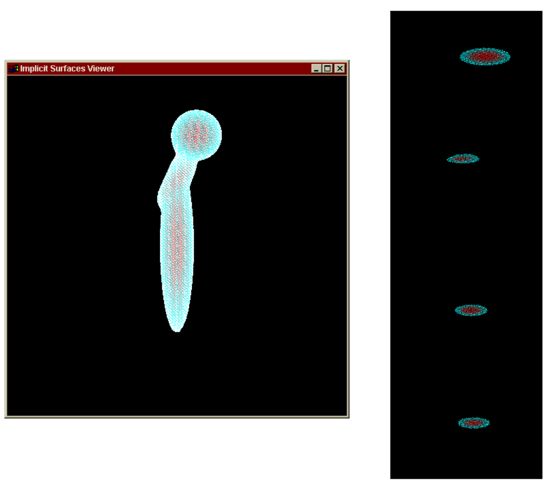
Slicing of Hip Socket Implant



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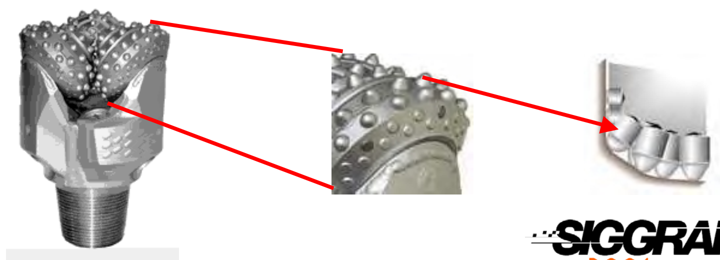
Tungsten Carbide/Cobalt Drill

Drill inserts for petroleum industry

- Molded ceramic, very brittle
- Need abrasive surface, ductile inner core



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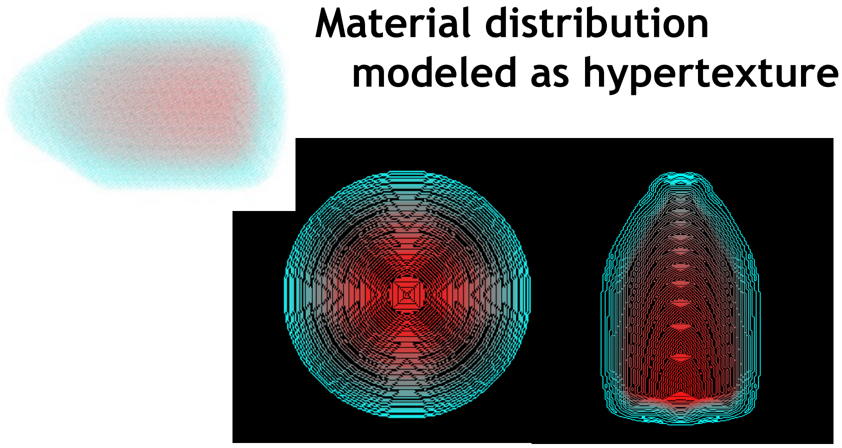
Multiple Material Drill Model

Material distribution modeled as hypertexture



Sliced material and geometry

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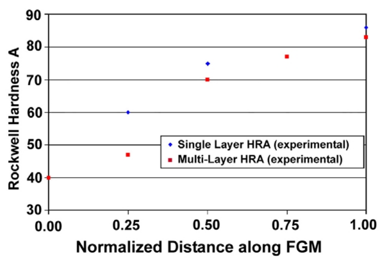
Prototype MMSLS Workstation

One-dimensional material grade

- Powders screw-fed into mixing chamber
- Mixed by impeller
- Deposited in front of roller for spreading



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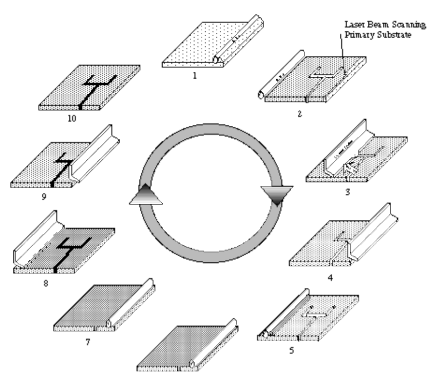
Discrete MMSLS Workstation Concept

- First powder deposited and scanned
- Unsintered powder removed (vacuum)
- Second powder deposited and scanned
- Unsintered powder removed



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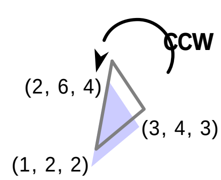
3D Hardcopy:
Software and Interchange Issues

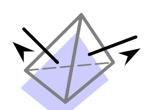
Sara McMains
U.C. Berkeley

The STL Format

De-facto industry standard
Boundary representation
Triangular facets



- Explicit vertex coordinates (not shared)
- Counter-clockwise enumeration



Surface normal for each facet

- Points to exterior of object (supposedly)

STL File of a Cube

```
solid ascii
 facet normal 1.000000e+00 0.000000e+00 0.000000e+00
   outer loop
     vertex 1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal 1.000000e+00 -0.000000e+00
0.000000e+00
   outer loop
     vertex 1.000000e+00 -1.000000e+00 1.000000e+00
     vertex 1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal 0.000000e+00 1.000000e+00 0.000000e+00
   outer loop
     vertex -1.000000e+00 1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 1.000000e+00 1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal 0.000000e+00 1.000000e+00 -
0.000000e+00
   outer loop
     vertex 1.000000e+00 1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
facet normal 0.000000e+00 0.000000e+00 1.000000e+00
   outer loop
     vertex -1.000000e+00 -1.000000e+00 1.000000e+00
     vertex 1.000000e+00 -1.000000e+00 1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal -0.000000e+00 0.000000e+00 1.000000e+00
   outer loop
     vertex -1.000000e+00 1.000000e+00 1.000000e+00
     vertex -1.000000e+00 -1.000000e+00 1.000000e+00
     vertex 1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
facet normal -1.000000e+00 0.000000e+00 0.000000e+00
   outer loop
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 -1.000000e+00 1.000000e+00
     vertex -1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal -1.000000e+00 0.000000e+00 0.000000e+00
   outer loop
     vertex -1.000000e+00 1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 1.000000e+00 1.000000e+00
   endloop
 endfacet
facet normal 0.000000e+00 -1.000000e+00 0.000000e+00
   outer loop
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 -1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal 0.000000e+00 -1.000000e+00 0.000000e+00
   outer loop
     vertex -1.000000e+00 -1.000000e+00 1.000000e+00
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 -1.000000e+00 1.000000e+00
   endloop
 endfacet
 facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
   outer loop
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 -1.000000e+00
   endloop
 endfacet
 facet normal 0.000000e+00 0.000000e+00 -1.000000e+00
   outer loop
     vertex 1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex -1.000000e+00 -1.000000e+00 -1.000000e+00
     vertex 1.000000e+00 1.000000e+00 -1.000000e+00
   endloop
 endfacet
end solid
```

STL Shortcomings

Redundant

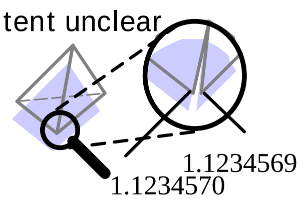
- Repeats vertex coordinates
- Exterior specification

No way to specify solid or surface properties

No units

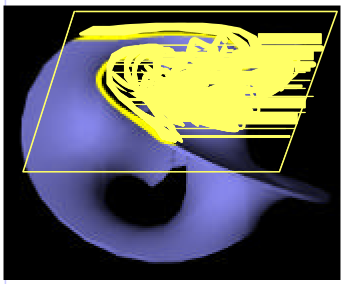
No connectivity (“topology”) information

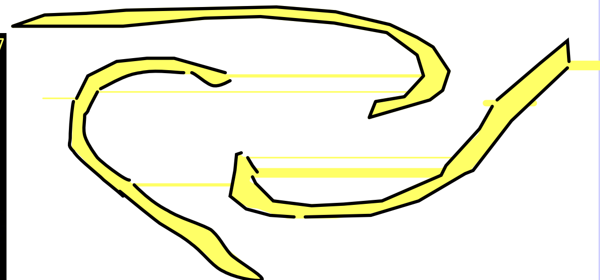
- Designer’s intent unclear
- Cracks



Scanning

When a good build goes bad...





Slice 463

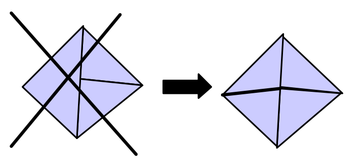
Model Requirements

Water-tight boundary

- No cracks

No T-junctions

- Vertex-to-vertex rule



Consistent triangle orientations

Positive coordinates

- Some systems automatically translate part

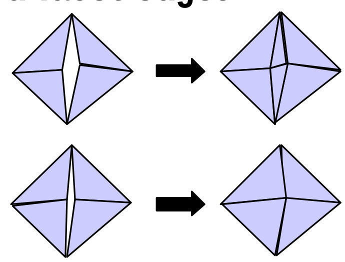
File Repair Techniques: Local

Triangulate between unmatched facet edges

- Bohn and Wozny '92
- Barequet and Sharir '95

Merges edges for small cracks, Triangulate remaining holes

- Barequet and Kumar '97



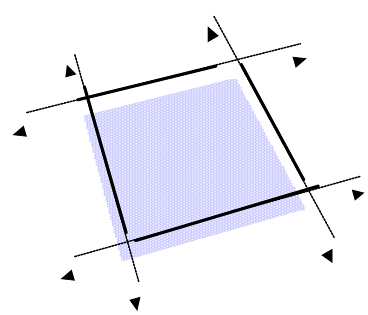
Adding triangles may introduce intersections; Best match problem NP complete

File Repair Techniques: Global

Build a BSP tree, identify solid regions, output boundary

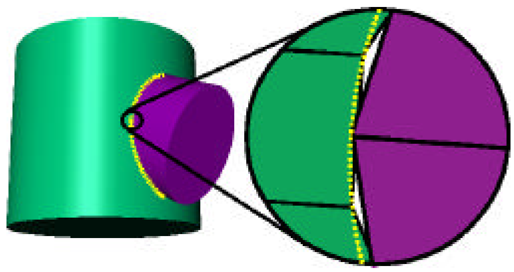
- Murali & Funkhouser '97

Scalability issues



One Source of Cracks

Approximating Boolean trim curves



Better STL Generation

Curved patch to STL conversion without gaps:

- **Match discretized trim curves,**
- **User-supplied tolerances**
  - Dolenc ’93
  - Sheng & Meier ’95
    - Prevent intersections when triangulating

Berkeley Solid Interchange Format (SIF)

Unevaluated Boolean constructs
- Evaluate in 2D after slicing instead
- Eliminate cracks at trim curves

Shared vertices provide connectivity info
- VRML style

Constructs for solid & surface properties

Mandatory units

http://www.cs.berkeley.edu/~ug/sif

SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Subdivision Surfaces

Easy to create water-tight meshes of arbitrary topology!

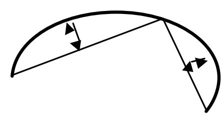
Subdivide after file transfer based on machine resolution

Contact compact (Jordan Smith)

SIGGRAPH 2001 EXPLORE INTERACTION

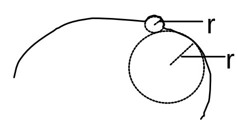
Mesh Generation

Most CAD packages let you specify error:



Pro/ENGINEER:
“Chord Height”
SDRC I-DEAS:
“Absolute Facet Deviation”

Pro/ENGINEER:
“Angle Control” ?



If radius r < partsize/10,
Chord Height' =
Chord Height * (10 * r/partsize)?

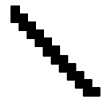
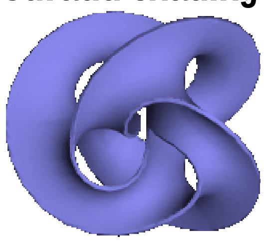
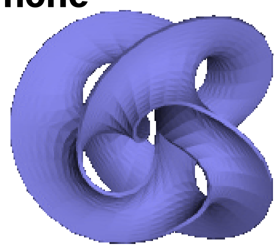
The Role of Mesh Simplification

Avoid if LM software can handle big files!
Go back to original model if possible.
Otherwise, iterative edge collapse approach:

- Preserves part topology
- Edges to collapse chosen based on original mesh, not original model

Resolution:
Computer Graphics vs. LM

Computer Graphics	LM
72 dpi CRT	up to 2000 lpi, up to 3000 dpi
Anti-aliasing	none
Gouraud shading	none

Faster Builds

Is this *rapid* prototyping?

2.5”, 15hrs

3.5”, 20hrs

3.0”, 25 hrs

Fused Deposition Modeling parts

Thin Walls

Speed up vector-scan LM

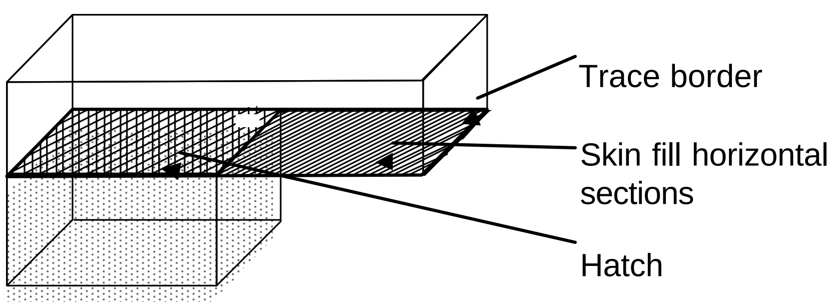
- Build time ~ vector scan length

Basic idea:

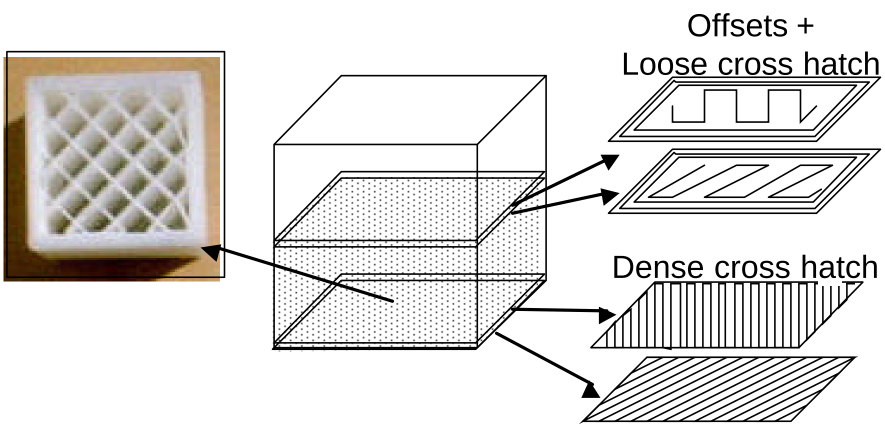
- Dense "thin wall" for part exterior
- Loose cross hatch for interior

Stereolithography Scan Patterns

Trap liquid in interior
Harden in Post-Curing Apparatus

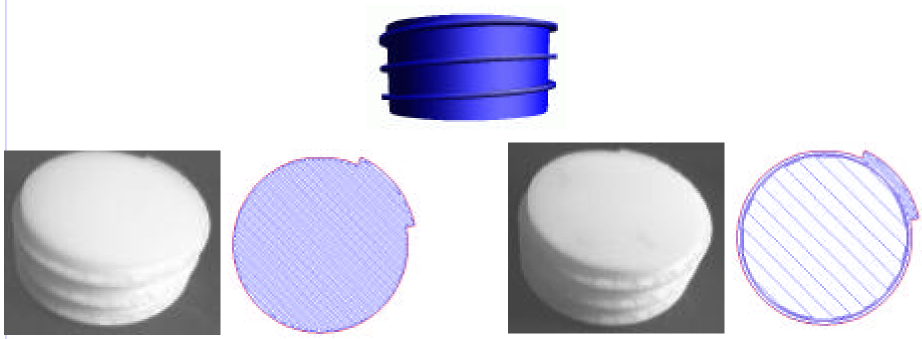


FDM QuickSlice™ Rapid Build



SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Thin Wall Speedup: Bolt Part



QuickSlice “fast build"

- Build time: 8h,24m
- Material: 22.1 m

Berkeley thin-wall method

- Build time: 3h,52m (46%)
- Material: 7.6 m (34%)

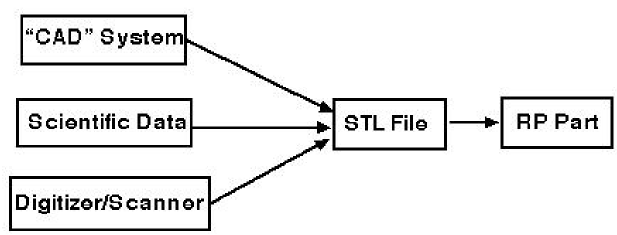
SIGGRAPH 2001 EXPLORE INTERACTION

Errors, Tolerances, and Aliasing Effects

Mike Bailey
San Diego Supercomputer Center
University of California San Diego
`mjb@sdsc.edu`

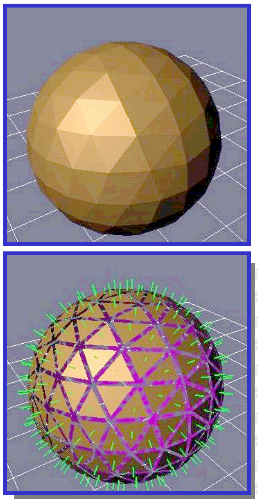
CENTER FOR VISUALIZATION PROTOTYPES
AT THE SAN DIEGO SUPERCOMPUTER CENTER

Where Do Part Geometries Come From?



The STL File Format

Triangles + Normals:



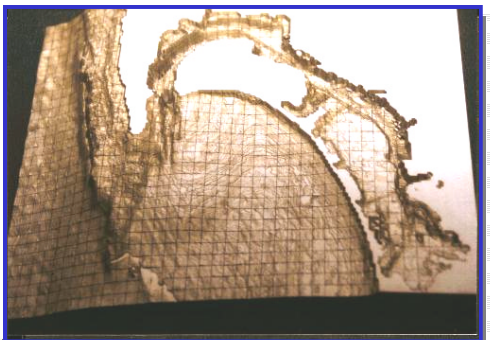
```
solid
  facet normal -0.62 -0.77 -0.12
    outer loop
      vertex 2.309218 0.639900 0.000000
      vertex 2.346300 0.609991 0.000000
      vertex 2.322692 0.621243 0.049971
    endloop
  endfacet
  facet normal -0.64 -0.76 -0.11
    outer loop
      vertex 2.292096 0.639900 0.100000
      vertex 2.309218 0.639900 0.000000
      vertex 2.322692 0.621243 0.049971
    endloop
  endfacet

     . . .

  facet normal  0.00  0.00  1.00
    outer loop
      vertex 2.568488 5.119200 4.500000
      vertex 2.346300 5.119200 4.500000
      vertex 2.559600 5.118925 4.500000
    endloop
  endfacet
endsolid
```

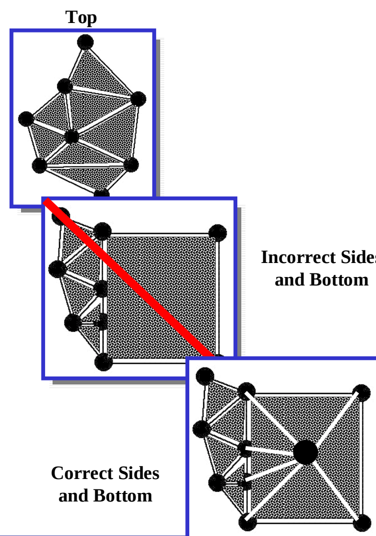

What is Typically Wrong with STL Files?

- **Violate STL vertex-to-vertex rule**
- **Normals inverted**
- **Cracks**

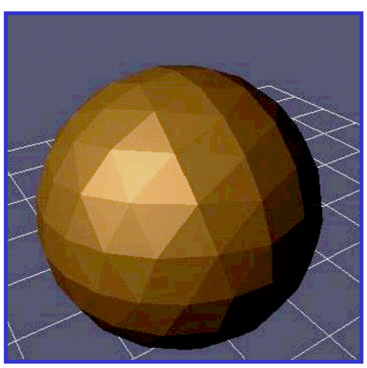
Vertex-to-Vertex Rule

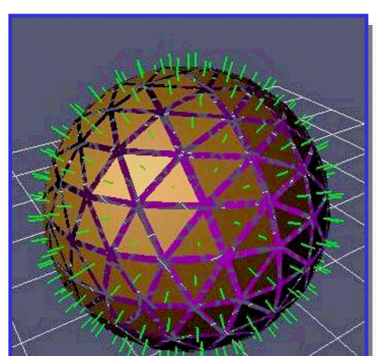
"All edges must bound two and only two triangles."



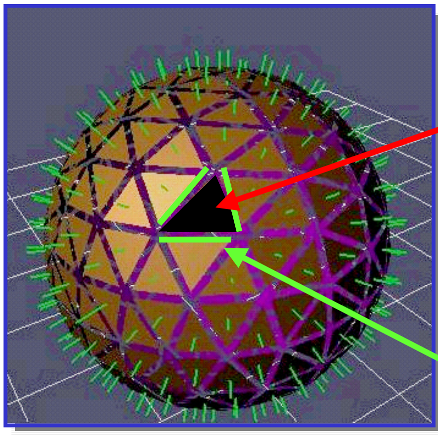


Normals Must Be Outward-Facing





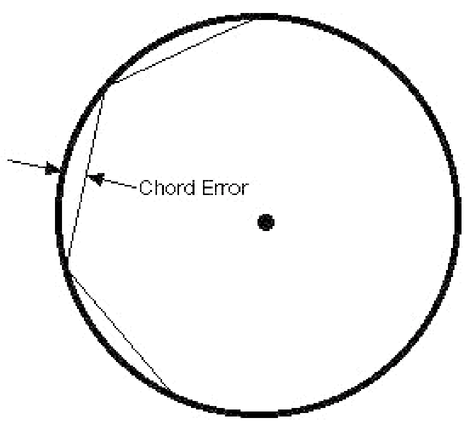
There Can be No Cracks in the Model



Missing triangle

3 Crack Edges

Tolerances of the Triangular Part to the Real Geometry: Chord Error



We also measure tolerances in surface area and volume

Tolerances of the Triangular Part to the Real Geometry: A Cylinder

# Triangles	Chord Error	Surface Area Error	Volume Error
10	19.10%	6.45%	24.32%
20	4.89%	1.64%	6.45%
30	2.19%	0.73%	2.90%
40	1.23%	0.41%	1.64%
100	0.20%	0.07%	0.26%

Tolerances of the Triangular Part to the Real Geometry: A Sphere

# Triangles	Chord Error	Surface Area Error	Volume Error
20	83.49%	29.80%	88.41%
30	58.89%	20.53%	67.33%
40	45.42%	15.66%	53.97%
100	19.10%	6.45%	24.32%
500	3.92%	1.31%	5.18%
1000	1.97%	0.66%	2.61%
5000	0.39%	0.13%	0.53%

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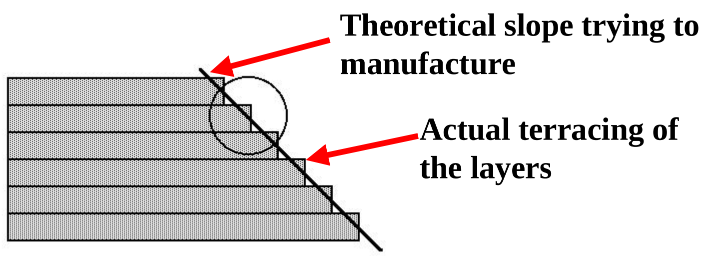
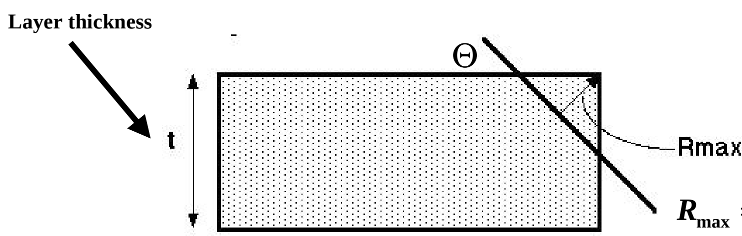
Aliasing in Layered Parts



How Much does the Actual Terracing Differ from the Theoretical Slope?



$$R_{\max} = \frac{t}{2}\cos\Theta$$

For a slope angle of 45º:

$$R_{\min} = 0 \qquad R_{\max} = \frac{t}{2\sqrt{2}} \qquad R_{avg} = \frac{t}{4\sqrt{2}}$$

How Much does the Actual Terracing Differ from the Theoretical Slope?

Using LOM paper (.0042”) as the layer thickness

Slope Angle (deg)	Rmax (in.)	Ravg (in.)
~0	.0021	.0011
10	.0021	.0010
20	.0020	.0010
30	.0018	.0009
40	.0016	.0008
50	.0013	.0007
60	.0011	.0005
70	.0007	.0004
80	.0004	.0002
90	.0000	.0000

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Thank You !

Mike Bailey
`mjb@sdsc.edu`

http://www.sdsc.edu/~mjb
http://cvp.sdsc.edu

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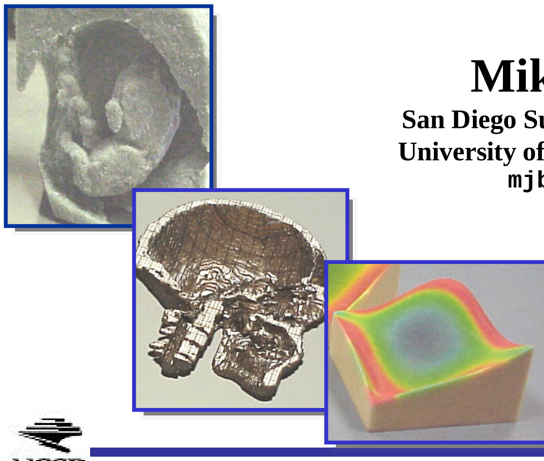
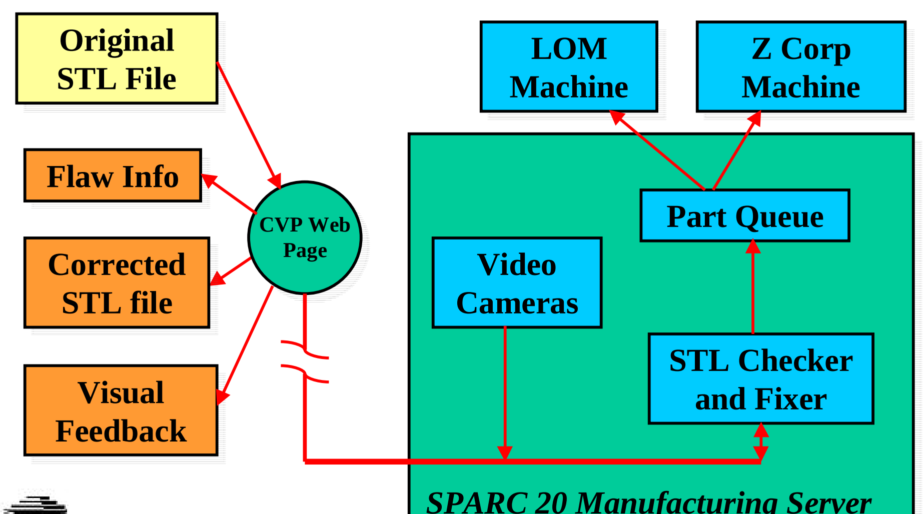
The Use of Solid Freeform Fabrication as a Visualization Display Tool



Mike Bailey
San Diego Supercomputer Center
University of California San Diego
`mjb@sdsc.edu`

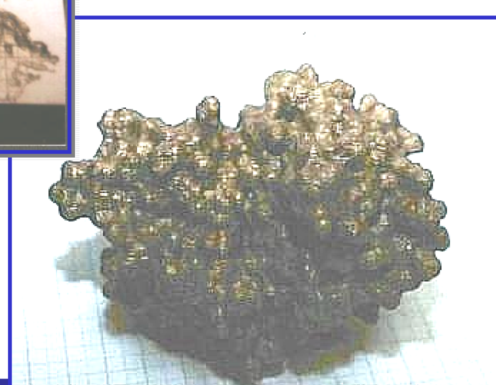
The Center for Visualization Prototypes (CVP) Project



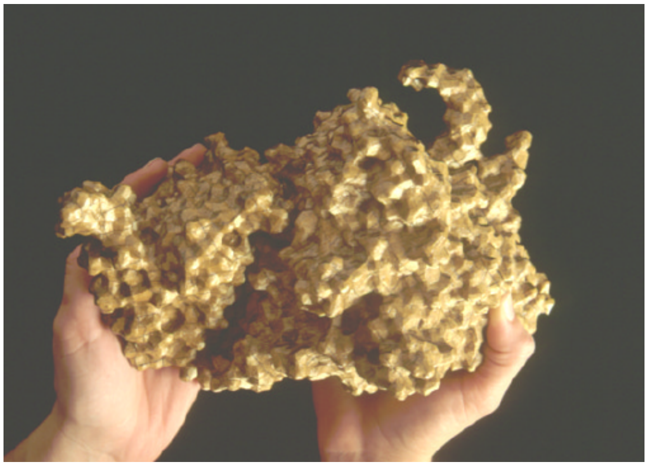
A Gallery of CVP Projects

San Diego Bay Bathymetry

Protein Kinase



Molecular Docking



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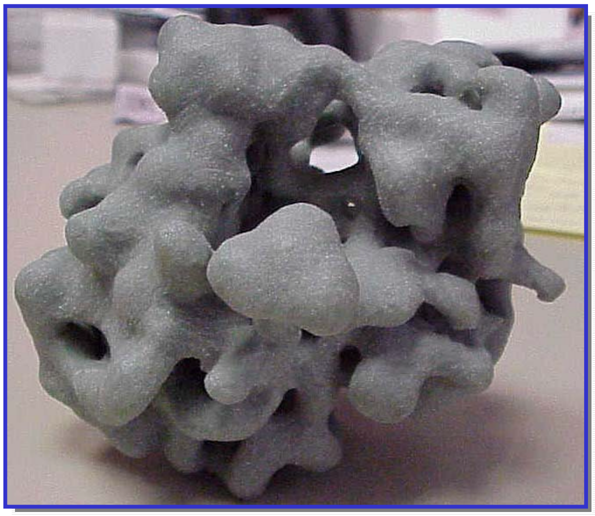
Ribosome



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3D Ultrasound

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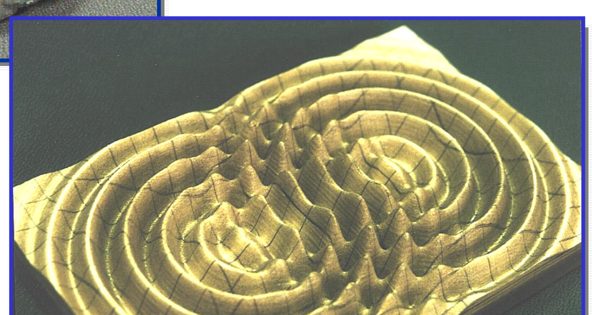

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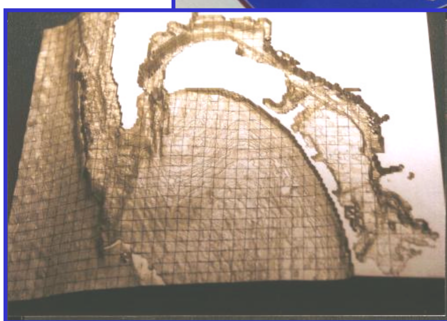
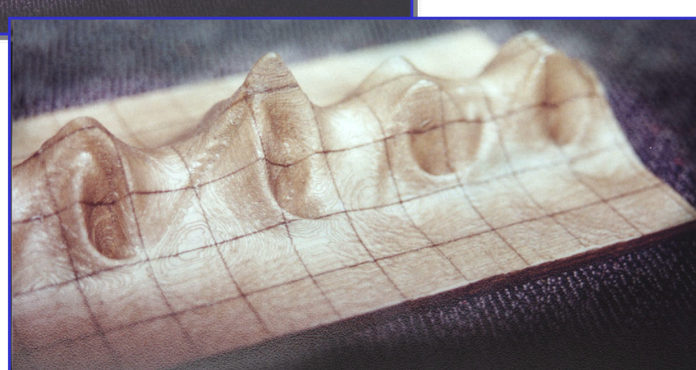
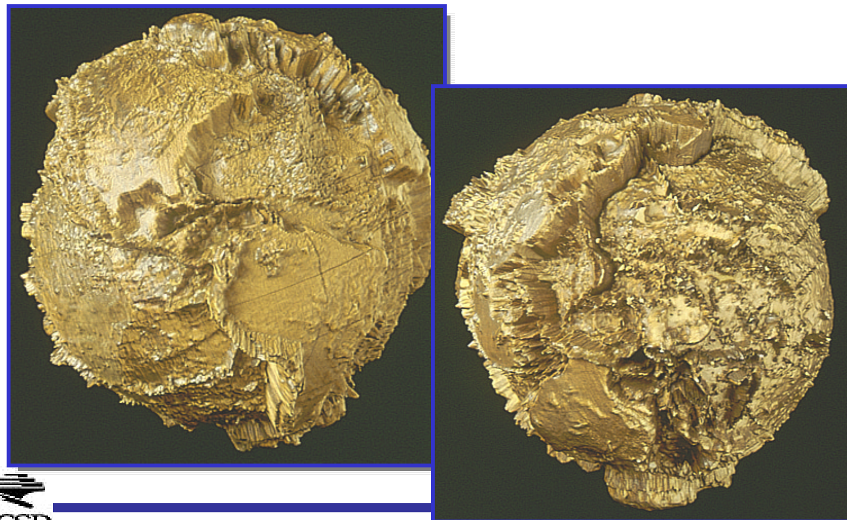




Give Us a Day, We’ll Give You the World :-#)



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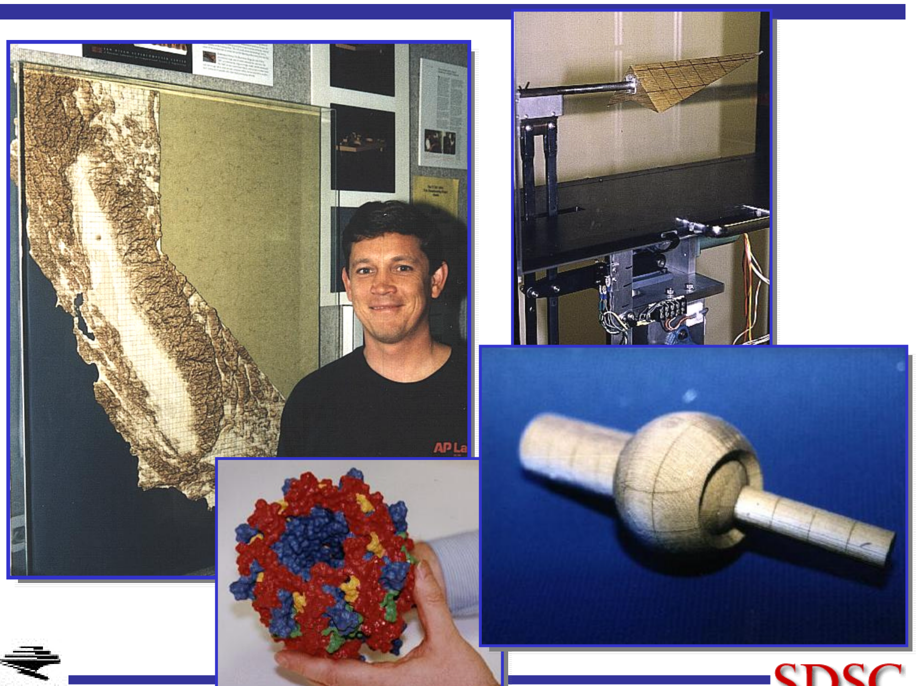

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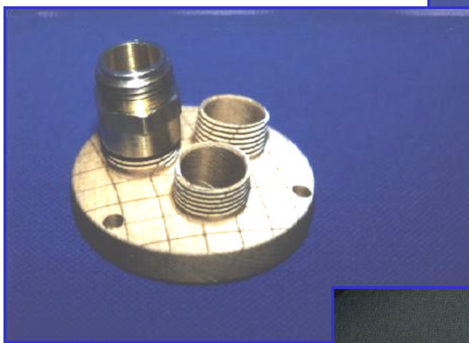

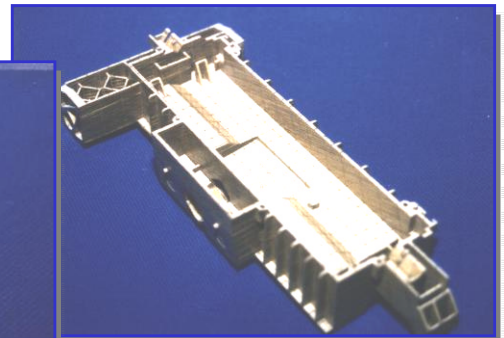

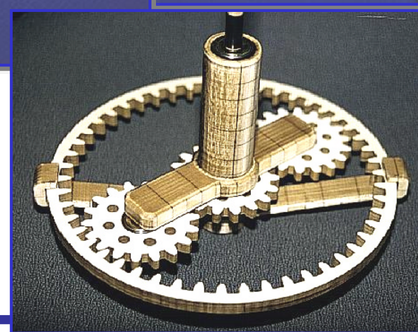

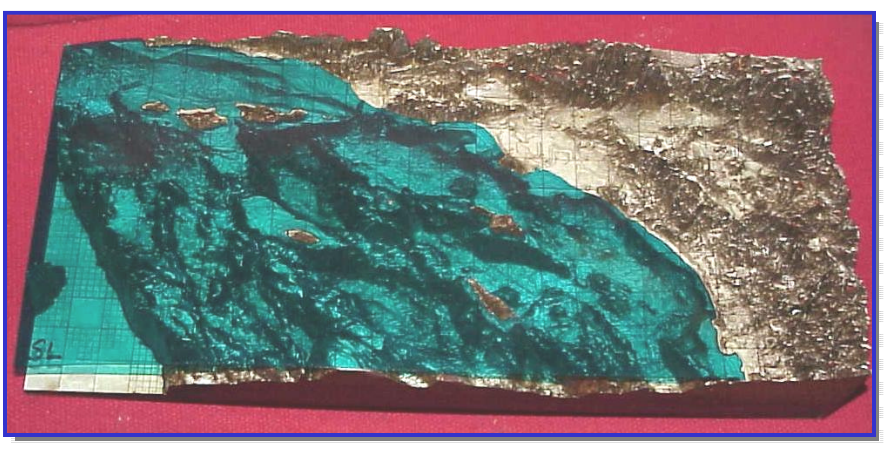

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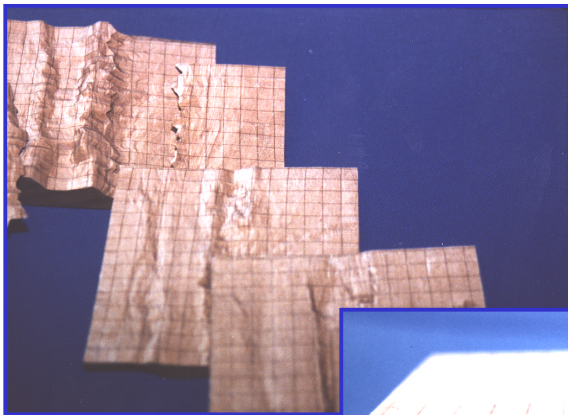
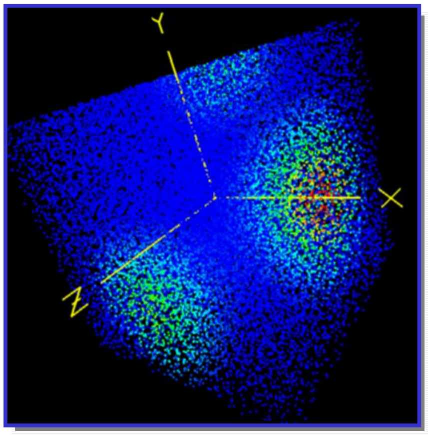


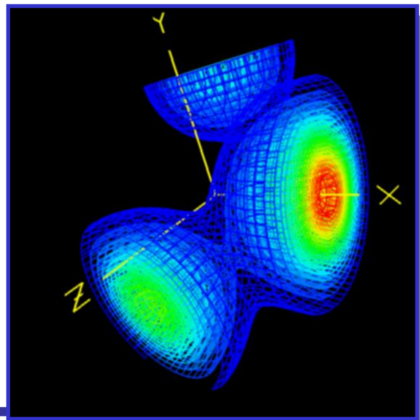
Manufacturing Isovolumes

Interlocking Isovolume Example: Three “ Hotspots”

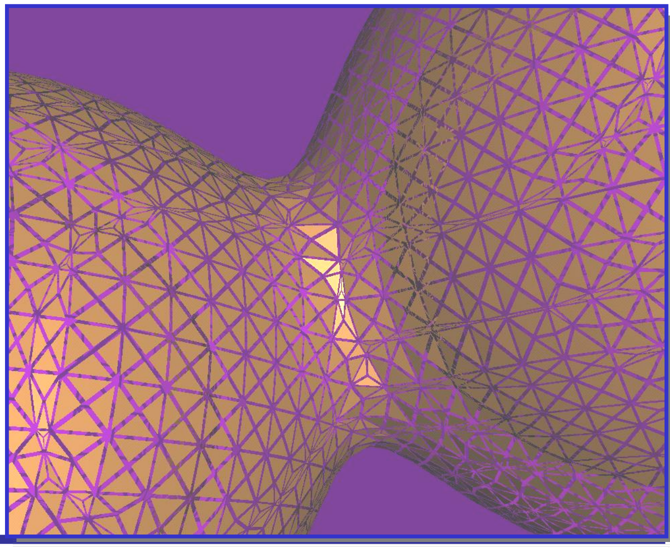


Jittered Point Cloud

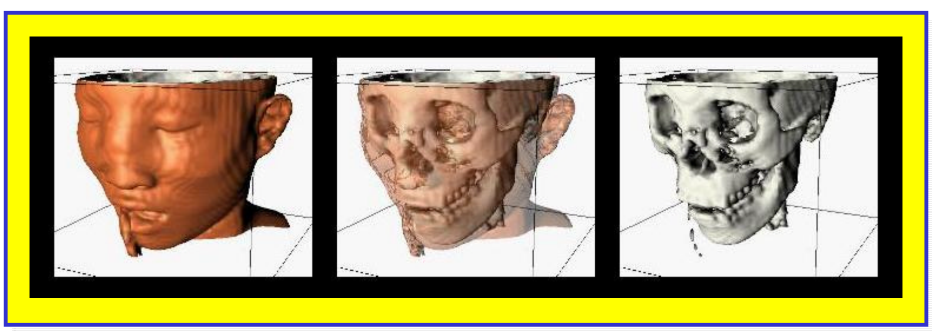
Wireframe Isosurfaces

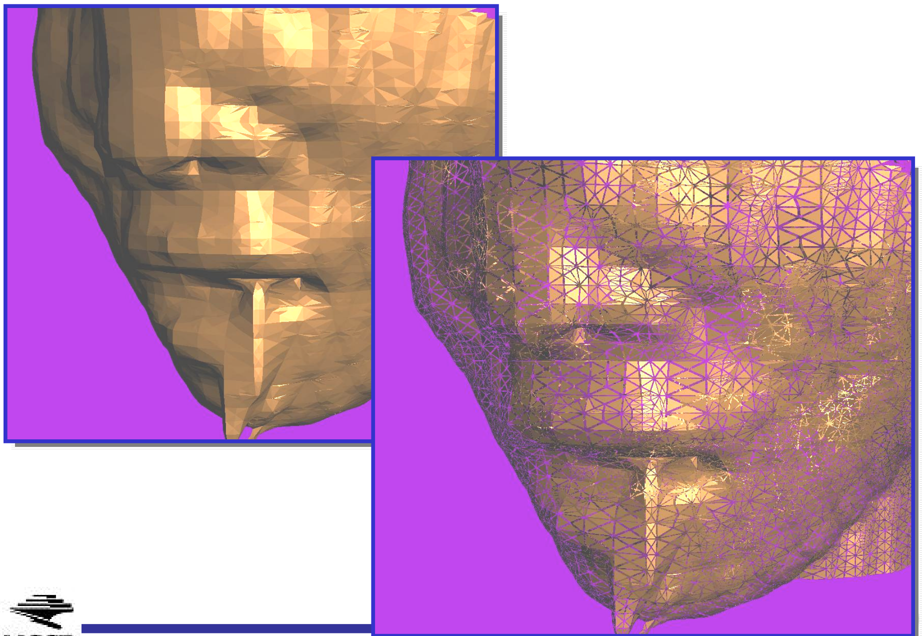


Triangulation of the Outer Isovolume



Isovolume Example: VTK Volume Data



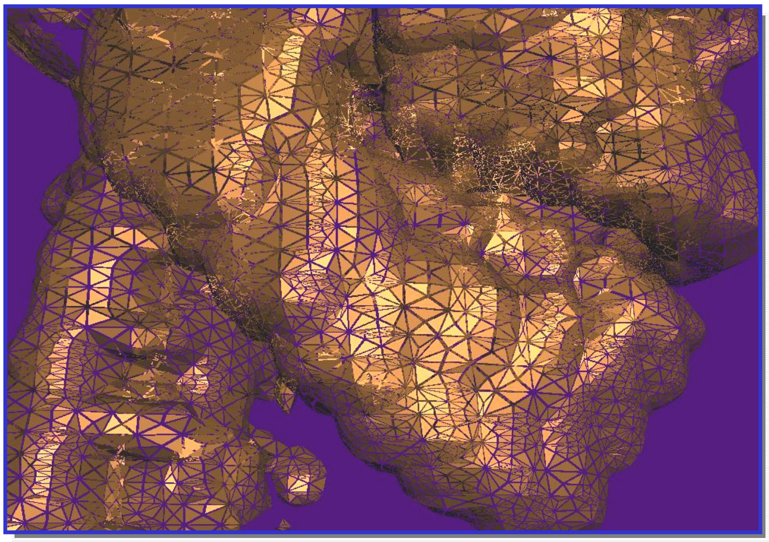


UCSD University of California San Diego

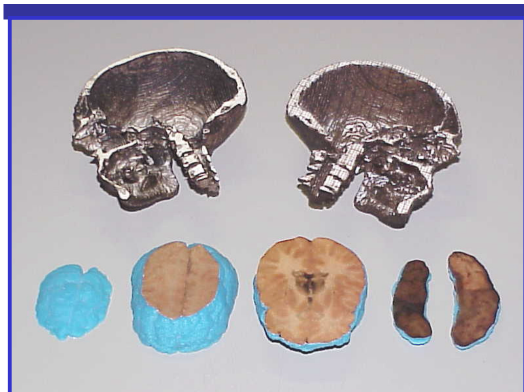
San Diego Supercomputer Center SDSC

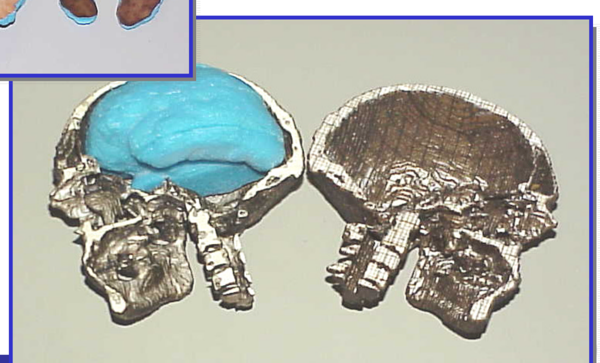
UCSD University of California San Diego

San Diego Supercomputer Center SDSC



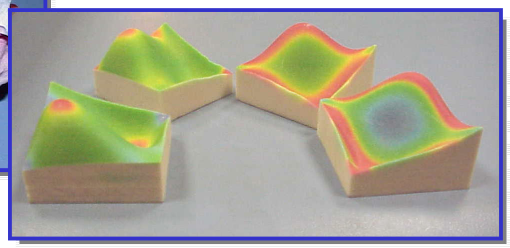
UCSD University of California San Diego San Diego Supercomputer Center SDSC





UCSD University of California San Diego San Diego Supercomputer Center

The Color Z Corporation Machine has Created many new Possibilities



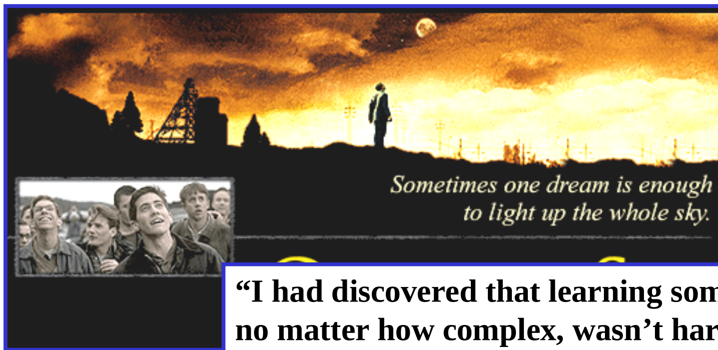
University of California San Diego

San Diego Supercomputer Center

University of California San Diego

San Diego Supercomputer Center

3D Makes Learning Fun !



"I had discovered that learning something, no matter how complex, wasn't hard when I had a reason to want to know it."

-- Homer Hickam, Jr., *The Rocket Boys*

Visualization in
9th Grade Earth Science

UCSD Student Project Example

Center for Visualization Prototypes

- Funding to make free models for visualization research
- Contact me (**mjb@sdsc.edu**) for details or go to the web site: **http://cvp.sdsc.edu**

Thank You !

Mike Bailey
mjb@sdsc.edu

http://www.sdsc.edu/~mjb
http://cvp.sdsc.edu

CENTER FOR VISUALIZATION PROTOTYPES
AT THE SAN DIEGO SUPERCOMPUTER CENTER

What Can SFF Be Used For?

Use of 3D Hardcopy

What is 3d Hardcopy good for? (cont.)

- **Consumer Electronics Design Prototypes**
  ==> touch and feel !
- **Mathematical & Topoplogical Models**
  ==> visualization and understanding
- **Artistics Parts & Abstract Sculptures**
  ==> all-round visual inspection,
  including light and shadows.

My goal is to inspire you to put these SFF technologies to new and intriguing uses.

SFF

Consumer Electronics Prototypes

Role of 3D Hardcopy -- Part 1:

- **Packaging of various electronics components.**
- **Custom designed housing for other utility products.**

SFF

Prototyping Consumer Products

"Solarcator" and "Contact-Compact"

Two student-designed "products" in ME221

SFF

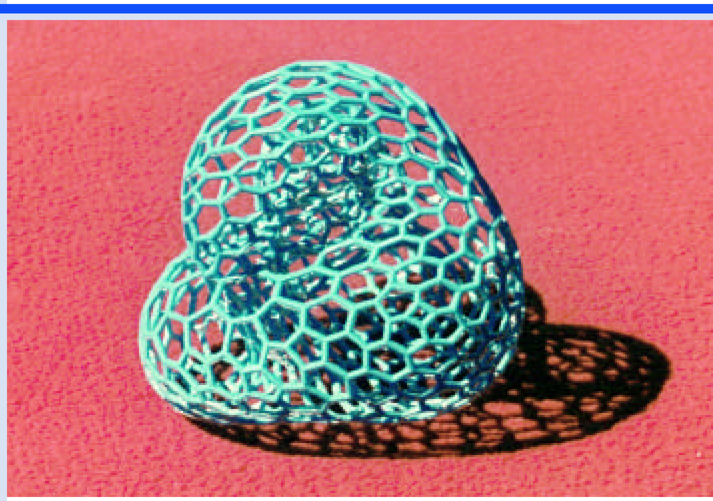
Geometrical / Topoplogical Models

Role of 3D Hardcopy -- Part 2:

- **Visualization of objects, when 2D is not quite enough.**
- **Self-intersecting surfaces.**
- **Projections of 4-D polytopes.**

SFF

Boy Surface

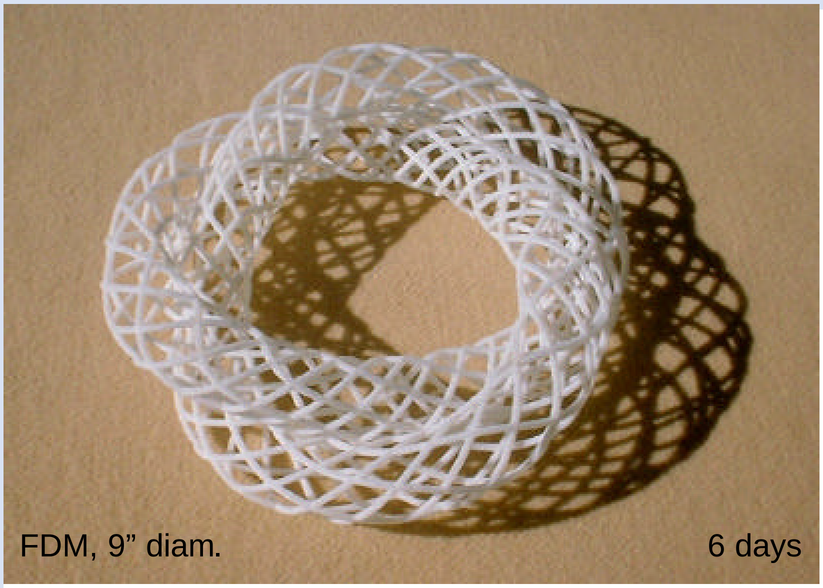


FDM
6” diam.
6 days

A model of the single-sided projective plane (with no rims and no singularities).

SFF

Triply-Twisted Figure-8 Klein Bottle



FDM, 9” diam.

6 days

SFF

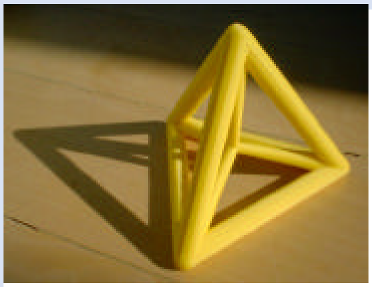
Morin Surface

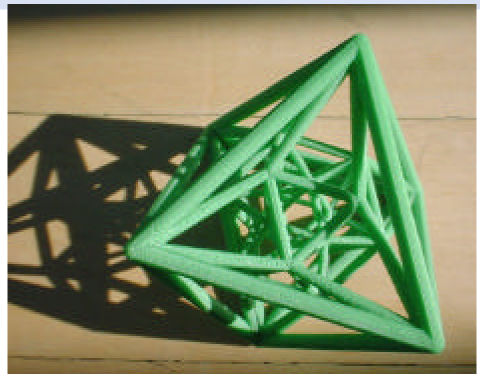
3D-P
6” diam
5 hrs.

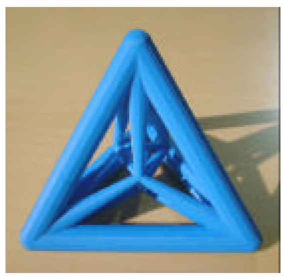
This is the half-way point of a sphere eversion (without causing creases or tears).

SFF

Small 4D Polytopes



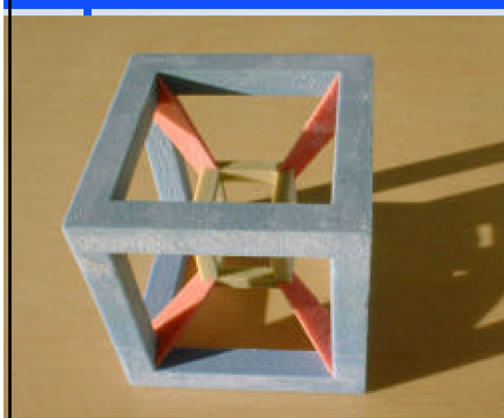




- 24-cell (hyper-octahedron)
- 4D simplex (five-cell)
- 4D cross polytope

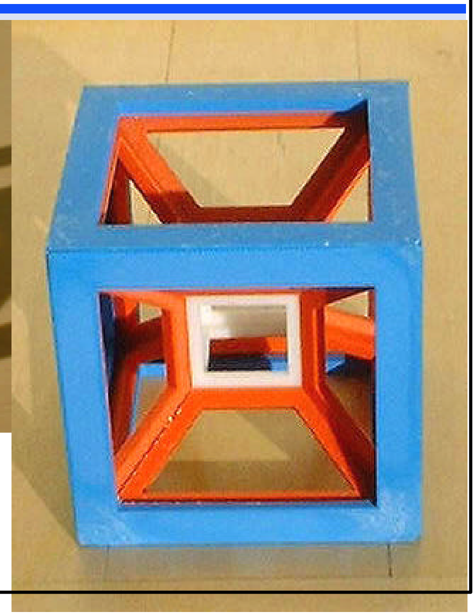
SFF

Two Ways to Make a Hypercube



3D Color Print

Assembly of
flat FDM parts ==>



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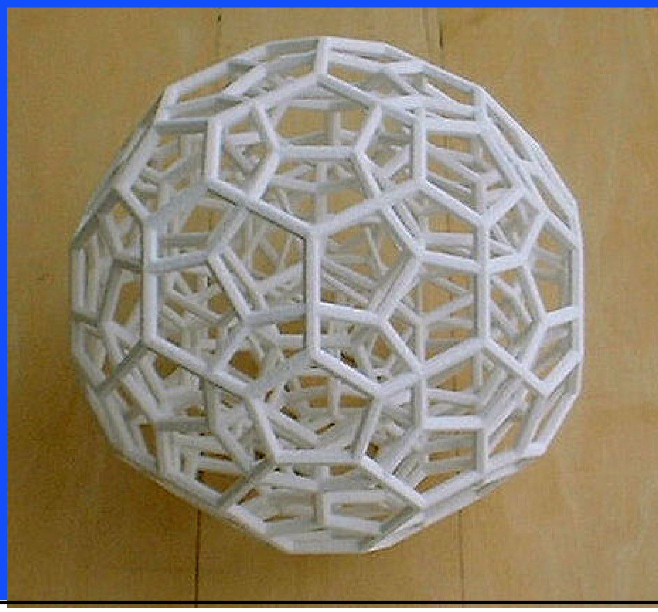
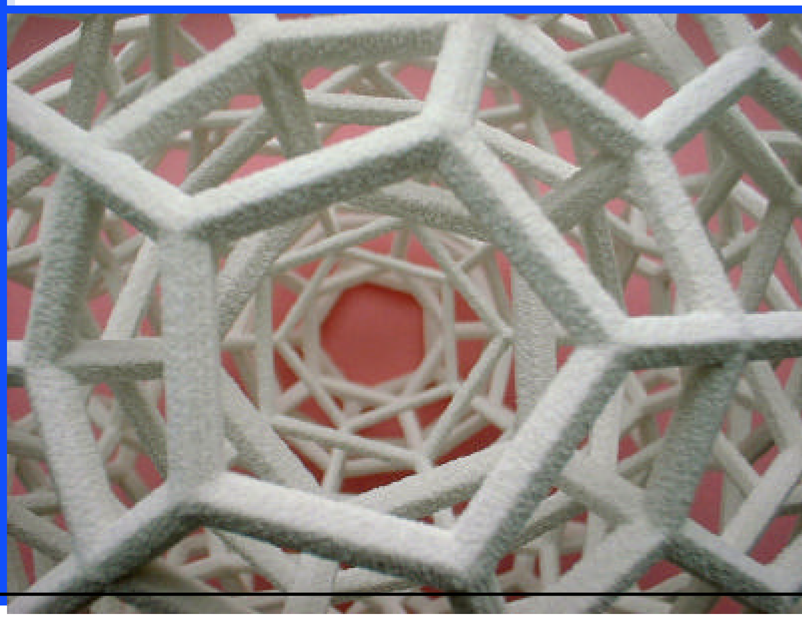
Parallel Projection of the 4D 120-Cell



- Zcorp,
- 6” diam.,
- 6hrs.

SFF

120 Cell -- Close-up



SFF

Artistics Parts, Abstract Sculptures

Role of 3D Hardcopy -- Part 3:

- **All-round inspection, including light and shadows.**
- **Parts that could not be made in any other way …**
- **Prototyping modular parts, before an injection mold is made.**

SFF

Escher Spheres 1

Assemblies of individual FDM tiles (2.5” diam.)

Escher Spheres 2

Multi-colored Zcorp parts:

no assembly needed!

Escher Spheres 3

Multi-colored Zcorp parts:

No support removal needed!

“Viae Globi” Sculptures

FDM maquettes of possible bronze sculptures

Family of Scherk-Collins Trefoils

SFF

Which Process Should You Pick?

Do you need a prototype (not just a model)?

- SLS, FDM (for robustness, strength).

Do you need a mold for a small batch?

- SLA (for smooth, hard surface).

Does part need multiple colors?

- 3D Color-Printing.

Does part have convoluted internal spaces?

- 3D-P, SLS, SLA (for easy support removal).

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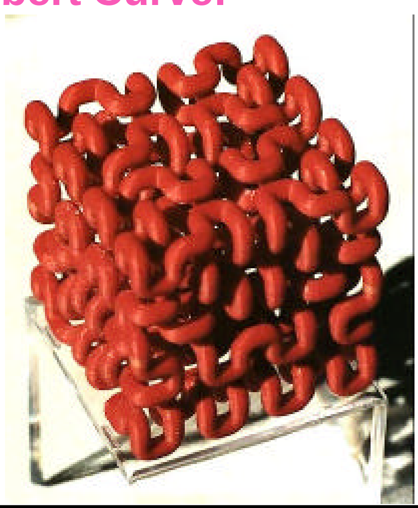
The Most Challenging SFF Part

3rd-order 3D Hilbert Curve:

- much weight
- much length
- no supports
- only two tube-connections between the two halves.



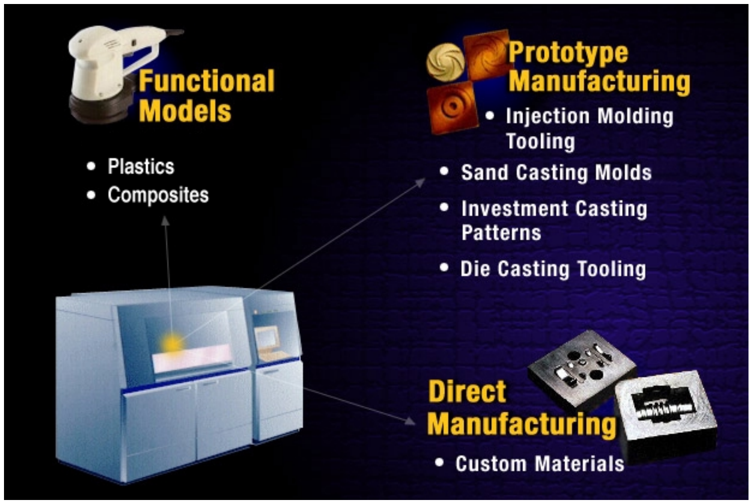
SFF

Pushing the Envelope ...

Informal Process Ratings Matrix

	Hollow Sphere	Hollow Sphere with Drain/Vent	2 Nested, Perforated Spheres	3D Hilbert Pipe	Preassembled Gear Mechanism
LOM	**(F)**	**F**	**F**	**D**	**F**
SLA	**(F)**	**D**	**C**	**B**	**D**
FDM	**(F)**	**F**	**C**	**C**	**D**
3D-P	**(F)**	**A**	**A**	**C**	**B**
SLS	**(F)**	**A**	**A**	**B**	**B**

Material Selection for SLS



SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Functional Models: Nylon-Based

Available Materials

- DuraForm™ Polyamide
- DuraForm GF*

Key Part Characteristics

- Good Toughness
- High Use Temperature = 163 - 188°C (DTUL @ 0.45 MPa)
- Good Solvent Resistance

SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Functional Models: Nylon-Based

Key Characteristics (cont.)

- Good Machinability
- Mechanical Joining, Adhesive Bonding, and Welding Are Possible
- Minimum Feature Size = 0.75 mm
- Typical Dimensional Tolerances = ±0.25 mm

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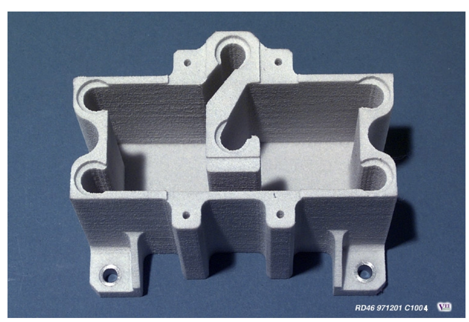
Case History: Nylon-Based Plastics Boeing/Rocketdyne

Product:

- Electrical Capacitor Box and Support Bracket for the International Space Station



Benefits:

- Glass Reinforced Nylon “Flight Certified” for Use on Spacecraft

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Case History: Nylon-Based Plastics
Boeing/Rocketdyne

Benefits (Continued):

- Strength Comparable to Injection Molded Plastic
- Tooling Time/Costs Avoided
- Entire Order of Capacitor Boxes (Several Dozen) Less Expensive Than Injection Molding Dies

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Functional Models: Elastomers

Available Material

- DuPont Somos® 201
- Distributed by DTM

Key Characteristics

- Elongation > 100%
- Good Solvent Resistance
- Upper Use Temperature > 100°C (Melting Temperature = 165°C)
- Typical Dimensional Tolerances = ±0.25 mm

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Functional Models: Elastomers

Somos 201 Application Examples:

- Gaskets
- Hoses
- Moldings
- Shoe Insoles/Outsoles

SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Prototype Manufacturing: Short Run Tooling

Available Material

- Copper PA System

Key Characteristics

- Typical SLS Process = 1-2 Days
- Finishing Can Be Done With Wet Sanding
- Typical Finishing / Fitting Time = 1-3 Days

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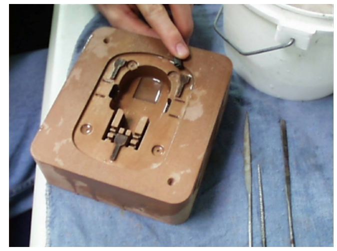
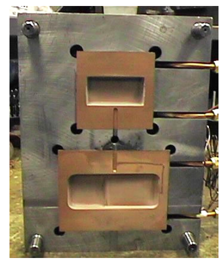
Prototype Manufacturing:
Short Run Tooling





Key Characteristics - Continued

- Good Thermal Conductivity
- Mold Several Hundred Parts With Common Plastics
  - PP, ABS, PC/ABS, PS, PE, GFPP
- Typical Dimensional Tolerances = ± 0.25 mm

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Case History: Short Run Tooling
BASTECH, Incorporated

Product

- Brake Fluid Reservoir for an Automotive OEM Client

Benefits

- Quickly Produced Two Molds With Multiple Inserts
- Provided Customer 75 Parts Molded in Polypropylene
- One-fourth the Cost, One-half the Time Compared to Steel Tooling

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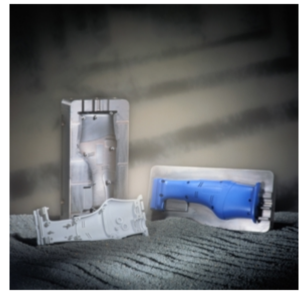
Prototype Manufacturing:
Long Run Tooling



Available Material

- LaserForm ST-100

Mold Inserts

- SLS Process - Stainless Steel with Thermoset Binder
- First Furnace Cycle - Sintering
- Second Furnace Cycle - Bronze Infiltration
- Final Finishing/Fitting

Prototype Manufacturing:
Long Run Tooling

Key Characteristics

- Typical SLS / Furnace Process = 3- 5 Days
- Typical Finishing / Fitting Time = 5-10 Days
- Material Can Be Machined, Welded, d Plate, Textured
- Overall Shrinkage = 0.2%

Prototype Manufacturing:
Long Run Tooling

Key Characteristics - Continued

- Strength and Hardness Similar to Steel
- Wear Characteristics Similar to Steel
- High Thermal Conductivity
- Pre-production Runs of >100,000 Parts From Most Plastics
- Typical Dimensional Tolerances = ± 0.125 to 0.25 mm

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Case History: Die Casting Tooling
Vaillant in Roding, Germany

Product:

- Prototype Pressure Die Cast Aluminum Parts Produced with RapidTool Mold Inserts

Benefits:

- 300 Parts Molded in Aluminum
- Reduced Development Time by 5 Weeks Over Conventional Machining

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Prototype Manufacturing:
Investment Casting Patterns

Available Materials

- TrueForm™ PM Polymer
- CastForm Polystyrene

Key Characteristics

- Low ash content (<0.02%)
- Behaves much like standard foundry wax

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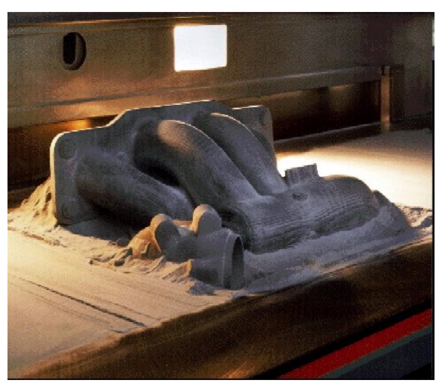
Prototype Manufacturing:
Investment Casting Patterns

Key Characteristics - Continued

- Works well with cast ferrous and non-ferrous metals, including Al, Mg, Zn, and Ti
- Easy pattern removal



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Prototype Manufacturing:
Investment Casting Patterns

Application Examples:

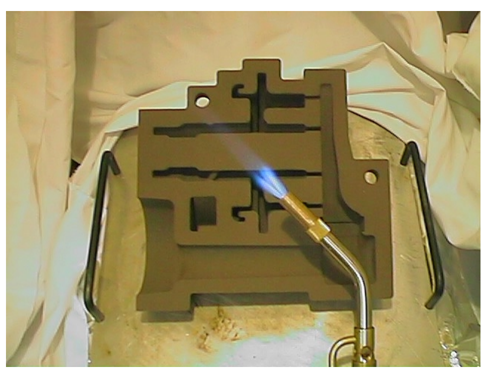
- Aerospace Parts
- Orthopedic Medical Devices
- Automotive Parts
- Golf Clubs

SIGGRAPH 2001 EXPLORE INTERACTION AND DIGITAL IMAGES

Prototype Manufacturing:
Sand Casting Cores & Molds

Available Materials:

- SandForm™ ZR II
- SandForm Si



Key Characteristics

- Shell Foundry Sand
- Complex Cores
- Molds with Integral Cores
- Dimensional Tolerances = ± 0.5 mm

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Medical Application:
Prosthetic Sockets

- 400,000 living limb amputees in US alone
- 60,000 new amputees added annually
- 97% could benefit from prostheses to assist locomotion
- 70,000 new prosthetists needed to meet needs with current technology
- Use of CAD/CAM techniques is only way to meet need

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SLS Manufactured Sockets

Benefits

- Custom-made prostheses sockets
- Integrated socket fitting
- Local control of geometry
  - Provide selective compliance for comfort
  - Provide stiffness for support

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Stiffness vs. Compliance

Solution: Double wall socket

- Outer wall provides stiffness for support
- Inner wall contains features that provide compliance
- Cannot be manufactured by vacuum forming (current method used at UT Health Science Center at San Antonio)

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Compliant Features

Several compliant features were tested, including helical springs and cantilever leaf springs

- Thicknesses ranged from 0.020” to 0.095”
- Helical springs could not be produced accurately

Final design: 60° triangular leaves 0.040” thick and 0.040” slots

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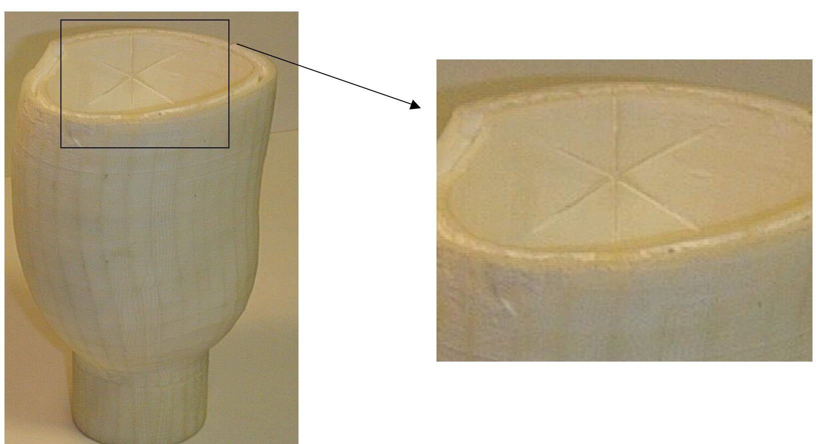
Completed Socket

Compliant Features



Fitted Socket

Clinical Results

- Patient reported higher socket comfort
- Self selected walking speed 3% higher
- Improve step length symmetry between prosthetic and intact limb
- 450 grams more mass than carbon fiber socket
  - Undetectable by patient
- Cost of fabrication was $1500
  - Needs to be $500 for commercial viability

Medical Applications:
Bone Implants

Objective

- Fabrication of calcium phosphate bone structures from CT scans
- Accurate construction of a complete facsimile bone structure within 24-48 hours

Processing Approach

- Convert CT scans/CAD data to SLS geometry data
- SLS of bioceramic using polymeric binder
- Firing and infiltration post-processing

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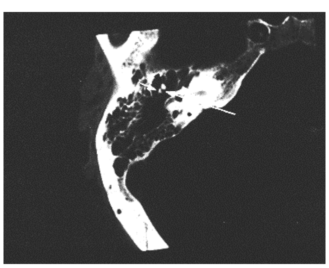
Medical Applications:
Bone Implants



Axial section CT scan of human temporal none

Bone structure reconstructed from CT data by SLS of Calcium phosphate

Status

- Two patents issues
- Clinical trials underway

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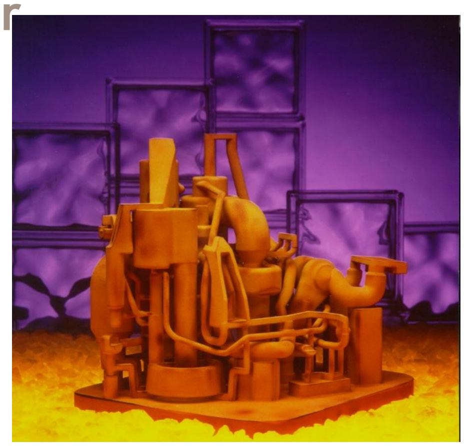
Case History: Sand Casting Tooling
Woodward Governor



Project Participants:
- Woodward Governor
- Clinkenbeard & Asso.
- Solidiform, Inc
- DTM

Product:
- Sand-cast aluminum fuel control system made using a SandForm Si core
- Part cast in Aluminum A356-T6

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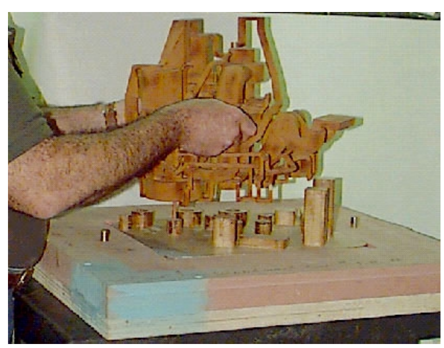
Case History: Sand Casting Tooling
Woodward Governor



Benefits:
- Direct production of core as single unit without tooling
- By conventional methods core array would comprise 60 pieces requiring tooling and assembly

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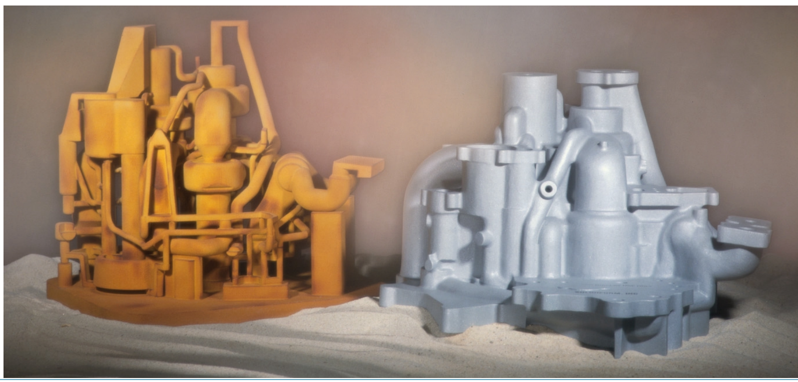
Case History: Sand Casting Tooling
Woodward Governor

Benefits (Continued):

- Castings produced 50% faster and cost 80% less than if cores were made using core boxes



Case Study:
Affordable ceramic metal matrix composites

Sponsored by Allison Engine Company

Objective

- Develop low cost indirect and direct SLS processing techniques to produce metal-ceramic composite turbine engine components

Material System

- Proprietary material composition consisting of superalloy and ceramics

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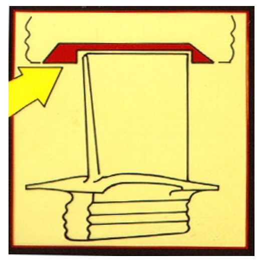
Case Study:
Affordable ceramic metal matrix composites

- Seals Working Gas Path
- Abrades into Porous Ceramic Track
- Forms Tight Shroud Seal
- Accounts for Thermal Expansion



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Tip Production

More than 100 tips produced

- 100% yield

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Case Study:
SLS with Low Cost HIP Post-Processing

Sponsors: ONR & Lockheed Martin Vought Systems

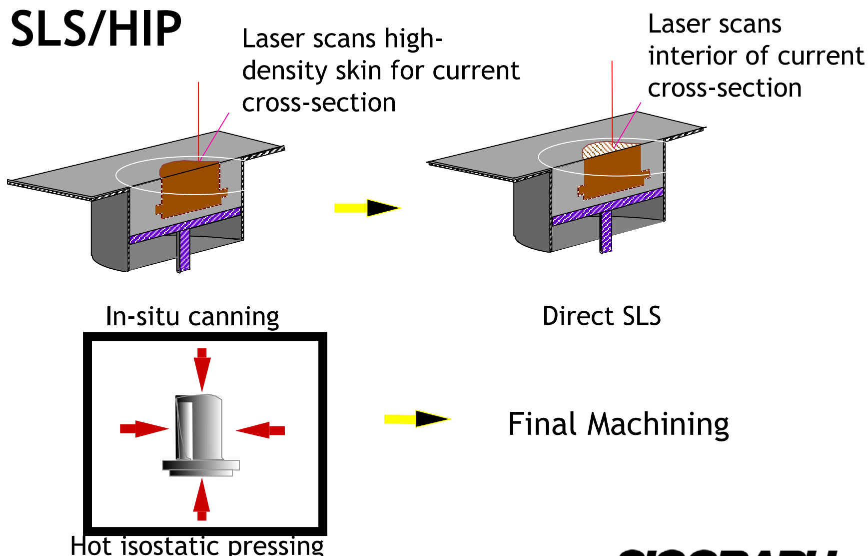
Objective

- Direct SLS of metal parts with integral, high density impervious skin for HIP post-processing

Candidate Material Systems

- Inconel 625
- Ti-6Al-4V

SLS/HIP



SLS/HIP advantages

- Secondary canning step eliminated by *in-situ* freeform canning and shaping.
- Adverse container-powder interactions eliminated.
- Post-HIP container removal step eliminated.
- Fewer processing steps result in reduced cost and shorter lead-time.

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U.S. Manufacturers of Rapid Prototyping Machines

3D Systems
(Stereolithography Apparatus--SLA--and ThermoJet solid object printer)
26081 Avenue Hall
Valencia, CA 91355
U.S. Toll Free Number: 888-337-9786
e-mail moreinfo@3dsystems.com
http://www.3dsystems.com/

DTM Corporation
(Selective Laser Sintering--SLS)
1611 Headway Circle
Building 2
Austin, TX 78754
phone: 512-339-2922
e-mail: marketing@dtm-corp.com
http://www.dtm-corp.com/home.html

Cubic Technologies, Inc. (took over from Helisys)
(Laminated Object Manufacturing--LOM)
1000 E. Dominguez St
Carson, CA 90746-3608
phone: 310-965-0006
email: info@CubicTechnologies.com
http://cubictechnologies.com/

Solidscape (formerly Sanders Prototype Inc.)
(PatternMaster and ModelMaker - thermoplastic ink-jetting plus milling)
316 Daniel Webster Highway
Merrimack, NH 03054-4115
phone: 603-429-9700
e-mail: precision@solid-scape.com
http://www.solid-scape.com/

Stratasys Inc.
(Fused Deposition Modeling--FDM and other thermoplastic technologies)
14950 Martin Drive
Eden Prairie, MN 55344-2020 USA
Toll Free: 888-480-3548
phone: 952-937-3000
e-mail: info@stratasys.com
http://www.stratasys.com/

Z Corporation
(3D Printing, color option available)
20 North Avenue
Burlington, MA 01830
phone: 781-852-5005
e-mail: sales@zcorp.com
http://www.zcorp.com/

A Few Service Bureaus

SLS and SLA
Accelerated Technologies, Inc.
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Austin, Texas 78754
(512) 990-7199
ati@atiaustin.com
http://www.acceltechinc.com/

SLA
Metalcast Engineering
4800 Coliseum Way
Oakland, CA 94601
(510) 534-2320
barragan@metalcast.com
http://www.metalcast.com/

Solidscape Modelmaker II
Protoshape
3127 Branciforte Drive
Santa Cruz, CA 95065
(831) 429-8224
info@protoshape.com
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Cast metal parts using 3D Printing technology to produce molds
(Direct Shell Production Casting)
Soligen - Parts Now
19408 Londelius St.
Northridge, CA 91324
Phone number: (818) 718-1221
Fax Phone number (818) 718-0760
http://www.partsnow.com/

An extensive and frequently updated on-line listing of vendors and service bureaus can be found at:
http://www.cc.utah.edu/~asn8200/rapid.html

STL File Repair Software

Clemson University distributes its IVECS program, an "Interactive Virtual Environment for the Correction of STL files."
http://www.vr.clemson.edu/ivecs/

Anthony Martin distributes his STL repair program ADMesh with the GNU general public license. It has a command line interface and no viewing capabilities.
http://server.varlog.com/products/admesh

Igor Tebelev distributes his shareware program for viewing and repairing STL files.
http://ourworld.compuserve.com/homepages/igort/stlview.htm

NEST Technologies is the US distributor for DeskArtes' (University of Helsinki spin-off) software for STL file repair.
www.primenet.com/~nest

Delcam PLC sells a program called Trifix for STL file verification and repair.
http://www.delcam.com/trifix/trifix.htm